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Movement and Effects of Combined Sewer Overflow Sediments in Receiving Waters

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16. ABSTRACT

The research work described here was a joint effort of Colorado State University (CSU) and the Sutron Corporation. The study had two primary objectives. The first objective was to determine from available literature the characteristics of combined sewer overflow (CSO) sediments and the factors affecting their transport properties. The second objective was to make use of the information on characteristics to evaluate a current sediment model capable of predicting the fate of CSO sediments.

CSU conducted the literature search and evaluation necessary to meet the first objective. The Sutron Corporation selected a test study site on the Cuyahoga River between Akron and Cleveland, Ohio; collected limited field data; and used the characteristics of CSO sediments found by CSU to evaluate a sediment model. Sutron also conducted a literature search of sediment sampling and tracing techniques necessary for model application.

It was concluded from the model experiments that qualitative evaluation can be made concerning the fate of CSO solids which are primarily noncohesive sands. Semi-quantitative evaluations could be made if proper data from a particular CSO of interest could be obtained. Particularly important to the model are the size distribution and settling velocity characteristics of the CSO sediments.

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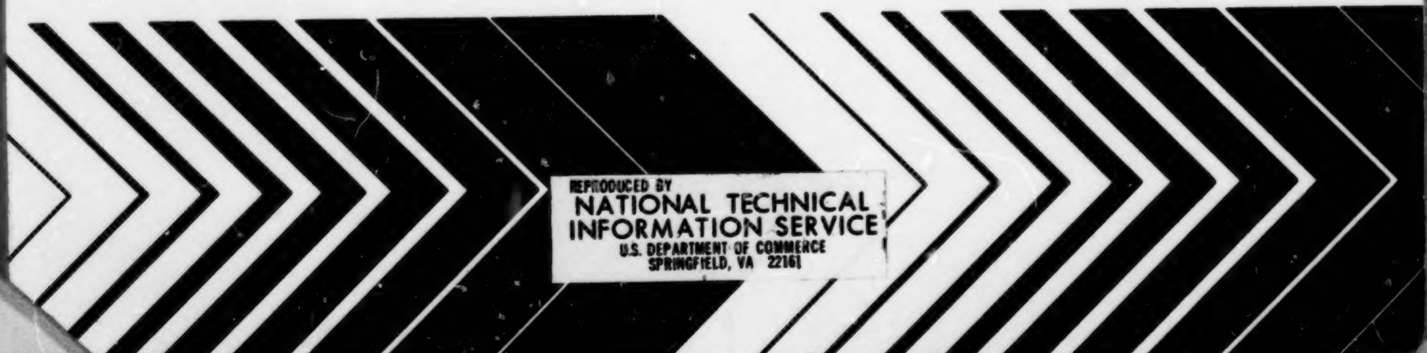

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August 1980

MOVEMENT AND EFFECTS OF COMBINED SEWER OVERFLOW SEDIMENTS IN RECEIVING WATERS

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FOREWORD

The Environmental Protection Agency was created because of the increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

This report investigates the current capability for determining the movement, fate, and effects of the sediment material from combined sewer overflows (CSO's). First, the available literature describing the characteristics of CSO sediments and their possible effects is reviewed. Next, the knowledge of these characteristics is used in conjunction with a sediment transport model to determine the movement of sediments in the Cuyahoga River between Akron and Cleveland, Ohio. Experiments are described wherein the model is used to predict the fate of sediment material from high flow bypass of the Akron municipal treatment plant under various flow conditions.

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ABSTRACT

The research work described here was a joint effort of Colorado State University (CSU) and the Sutron Corporation. The study had two primary objectives. The first objective was to determine from available literature the characteristics of combined sewer overflow (CSO) sediments and the factors affecting their transport properties. The second objective was to make use of the information on characteristics to evaluate a current sediment model capable of predicting the fate of CSO sediments.

CSU conducted the literature search and evaluation necessary to meet the first objective. The Sutron Corporation selected a test study site, collected limited field data, and used the characteristics of CSO sediments found by CSU to evaluate a sediment model. Sutron also conducted a literature search of sediment sampling and tracing techniques necessary for model application.

Combined sewer overflows are made up of urban surface runoff and sanitary sewage. The contribution of sanitary sewage to the total flow is negligible at times of peak flow in many cases, although its effects on time dependent changes in the CSO's may be important.

Urban surface runoff makes up the majority of a CSO. The characteristics of CSO sediment material for model development were thus taken to be those of street surface solids. The size distribution of street surface solids appear to be reasonably well defined log-normal distributions. In general, sizes range from fine to medium sand. Makeup of street surface solids is difficult to define from the available data, although sufficient data are available to make an initial approximation. A wide variety of constituents may be found, ranging from metallic elements to pesticides.

The effect of the chemical properties of the sediments on their transport characteristics has not been addressed in the literature to any great degree. Only broad general characteristics of the type of reactions, which might occur, can be made. Even less appears to be known concerning the effect of deposited or eroded materials on the biologic community. A good deal is known about what types of animal and plant life exists in streams but few studies specifically address the questions of being buried or deprived of light or any of the dozens of other effects related to sediments.

Sutron investigated the feasibility of modeling the movement of CSO sediments on 64.37 km (40 mile) reach of the Cuyahoga River between Akron and Cleveland, Ohio. The reach investigated was quite steep (slope = .00095). Two small diversion structures formed sediment trap areas. The downstream end of the reach included the Cuyahoga estuary into Lake Erie.

The sediment transport routines from a water shed model developed at CSU were combined with a linear implicit finite difference flow model for use in the feasibility study. Limited field data on sediment sizes and stream cross sections were gathered by Sutron. Hypothetical sediment loads from the high flow bypass of the Akron municipal treatment plant were developed from data obtained by CSU's literature search.

Experiments indicate that the movement of hypothetical sediment loads may be successfully modeled. Under normal low flow conditions, sediments accumulate near the bypass outfall. A flood of five-year recurrence interval will move course sediments from the outfall to the small trap areas. Fine material moves through the reach and settles in the estuary under all flow conditions.

It was concluded from the model experiments that qualitative evaluation can be made concerning the fate of CSO solids which are primarily noncohesive sands. Semiquantitative evaluations could be made if proper data from a particular CSO of interest could be obtained. Particularly important to the model are the size distribution and settling velocity characteristics of the CSO sediments. Several experiments were conducted with hypothetical sediments with specific gravities similar to elemental heavy metals. These experiments indicated that qualitative prediction of the fate of such materials is also possible. Flood frequency analysis combined with hypothetical flood hydrographs provided a useful tool for analyzing the fate and residence time of CSO sediment material deposits. A verification study for the model would be highly desirable. Most of the data used in this study was hypothetical. The model's ability to predict the fate of sediments can only be conclusively verified using data collected for that purpose.

Sutron's investigation of sampling and tracing techniques indicates that considerable information exists on sampling the suspended portion of stream sediment loads. No current network exists to accurately measure the portion which moves along the channel bed by rolling and sliding. This implies that reaches selected for model verification must be selected carefully to allow measurement of all material in suspension.

Tracing the movement of CSO sediment materials is possible but may be impractical. Radioactive tracers are highly developed and effective but environmentally objectionable. Fluorescent dye methods could probably be used but involve considerable labor and analysis costs. Results are qualitative in nature.

This report was submitted in partial fulfillment of Research Grant No. R806111 by Colorado State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of August 15, 1978 to August 14, 1979 and was completed March 3, 1980.

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MODEL PARAMETERS IN ORDER OF USE

EQUATIONS (1), (2), AND (3)

G_s = total sediment transport rate by volume, volume/time
∂x = section length
C = Sediment concentration by volume, volume/volume
A = river cross-section area, area
∂t = unit time
P = wetted parameter, cross-section length
z = net depth of loose soil, length
g_s = lateral sediment inflow, volume/unit length/time
Q = water flow rate, volume/time

EQUATION (4)

τ_c = sediment shearing stress, force/area
δ_s = empirical constant, range 0.01 to 0.06, used 0.047
γ_s = specific weight of sediment, weight/unit volume
γ = specific weight of water, weight/unit volume
d_s = particle diameter, length

EQUATIONS (5), (6), AND (7)

q_b = bed load transport rate, volume/unit width
τ_o = boundary shear stress acting on sediment particle, force/area
τ_c = critical sediment tractive force, force/area
a = empirical constant, used $8/(\sqrt{\rho}\ (\gamma_s - \gamma)$
b = empirical constant, used 1.5
ρ = density of water, mass/volume
f = Darcy-Weisbach friction factor, dimensionless
V = average flow velocity, length/time

EQUATIONS (8), (9), (10), AND (11)

C_ξ = sediment concentration at a distance above the bed, weight/volume

C_a^* = known sediment concentration at distance "a*" above the bed, weight/volume
R = hydraulic radius, area/wetted perimeter, length
ξ = height above bed, length
a^* = reference height above bed, length
w = parameter based on settling velocity and shear velocity, dimensionless
V_s = settling velocity of particle, length/time
U_* = shear velocity, length/time
τ_* = specific shearing stress, force/area

EQUATIONS (12) THROUGH (17)

U_ξ = point mean velocity at a distance above the bed, length/time
B_1 = empirical constant dependent upon roughness, dimensionless
n_s = Manning's number range 0.01 to 0.1, used 0.035
σ = ratio of sample distance above bed to hydraulic radius, dimensionless
G = ratio of reference distance above bed to hydraulic radius, dimensionless
a = thickness of bed layer equal to twice the size of the sediment, length

EQUATIONS (18) THROUGH (23)

J_i = Einstein's integrals, dimensionless
q_s = suspended sediment transport rate, volume/unit width
q_t = total sediment load, volume/unit width
G_c = sediment transporting capacity, volume/time

EQUATIONS (24) THROUGH (28)

F_a = adjusted fraction of sediment in the ith size
Z = loose sediment depth in each size fraction, length
F = original bed material percentage in each size fraction, dimensionless
D_{84} = size of sediment for with 84 percent of the sample is finer, length

EQUATION (29)

ΔZ^P = total potential changes in loose soil storage, length
D = total amount of detached soil, length
D_f = detachment coefficient, range 0.0 to 1.0
C^P = potential sediment load concentration, volume/volume
n = time index
j = location index

EQUATION (30)

Θ = travel time per distance, time/length
a' = space weight factor, usually set to 0.5, dimensionless
b' = time weight factor, usually set to 0.5, dimensionless

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SECTION 1

INTRODUCTION

STUDY BACKGROUND

Considerable effort has gone into the study of sewer systems and sewage treatment. Less is known, however, about the impact on receiving waters of material which escapes the sewer via urban stormwater runoff and combined sewer overflows (CSO's) during storm events. The study reported here investigates the current technology for modeling the movement of sediment materials from CSO's.

The original impetus for a study such as this was provided by a 1974 EPA report authored by the North Carolina Water Resources Research Institute (1). An intensive study was made of the runoff from a 1.67 square mile urban watershed in Durham, North Carolina. The urban runoff yield of chemical oxygen demand (COD) was equal to 91 percent of the raw sewage yield. The biochemical oxygen demand (BOD) was equal to 67 percent, and the urban runoff suspended solids yield was 20 times that contained in raw municipal waters for the same area. The study identified the "first flush" phenomena, wherein water quality may deteriorate drastically in the early period of storm runoffs as builtup pollutants are flushed from the system. The importance of sediments as a source of organic and inorganic pollutants was emphasized by the facts that plain sedimentation of the runoff resulted in 60 percent COD removal, 77 percent suspended solids removal, and 53 percent turbidity reduction.

The Durham study was limited to direct urban land runoff. When this runoff is collected in a combined sewer system and routed to a treatment plant, additional problems are encountered. It is uneconomical to design treatment facilities large enough to handle a once in 100 years storm flow plus the normal municipal sewage load. Thus, at some high flow rate provisions must be made to bypass the treatment facilities with a mixture of sanitary sewage plus urban runoff. This combined sewer overflow (CSO) material is characteristically dumped directly into a receiving water. The Durham study illustrates that discharging the CSO mixture is not very different from discharing raw sewage in the receiving water.

Field, Tafuri, and Masters (2) draw on the Durham study and cite an ongoing R & D study in Milwaukee, Wisconsin, which defines some of the CSO impact on receiving waters. Strong evidence is present that CSO discharges intensify dissolved oxygen (DO) sag and increase fecal coliform concentration. The Milwuakee study again defined the need for study of the impact of CSO material on receiving waters.

The adsorptive and absorptive capacities of CSO sediments has a significant effect on the pollution potentials of these sediments during periods of re-entrainment. Pitt and Field (3) have reported that little is known about either the short or long term toxic effects of urban stormwater runoff in a variety of waters and ecosystems. Since in some instances, large amounts of toxic materials such as heavy metals, pesticides, and PCB's are being discharged along with nontoxic biological and chemical materials, it is desirable to trace the route these materials take through a receiving water system.

OBJECTIVES

The studies described above indicate a need to study the paths by which CSO sediments and sediment materials move through receiving waters. The objectives of the study are to meet this need.

The two primary objectives of the study are to: (1) define the state of knowledge concerning the sediment transport characteristics of CSO sediments and (2) evaluate the capability of a sediment transport model to predict the fate of CSO sediments. Two secondary objectives are to: (1) summarize current knowledge of the impact of sediment materials on receiving waters and (2) describe sampling and tracing techniques which may be used to study the fate of CSO sediment materials.

SCOPE OF WORK

The scope of this study consists of five general areas with major emphasis on two. The two areas with major emphasis are: (1) a literature search to define the current state of knowledge of the quantities and characteristics of CSO sediments, and (2) an investigation of a combined flow-sediment transport model. The three remaining research areas are: (1) a literature search for knowledge concerning the impact of CSO sediments on receiving waters, (2) a literature investigation of the chemical interactions between various CSO sediment constituents and the receiving water, and (3) a literature investigation of sampling and tracing techniques.

ORGANIZATION AND CONDUCTION OF STUDY

Colorado State University conducted the major portion of the literature survey for CSO sediment characteristics and effects. The Sutron Corporation conducted the model investigation and the literature survey of sampling and tracing techniques.

Colorado State University used standard library search methods as well as computer keyword searches to identify pertinent references. All material concerning the transport characteristics of CSO sediments were summarized and forwarded to Sutron for use in the model study.

Sutron selected a 64.37 kilometer (40 mile) reach of the Cuyahoga River between Akron and Cleveland, Ohio for model application based on data availability and results of previous study (4). Sediment and flow data were obtained from USGS research. CSO flows from the Akron municipal treatment plant bypass were estimated based on the information gathered by CSU.

While Sutron was completing the model investigation, CSU summarized the available knowledge on interacting of CSO sediments and receiving waters. Sutron conducted a limited survey of sampling and tracing methods after completion of the model study.

Sutron combined all of the information provided by the literature survey with the results of the model studies to form the initial draft report. CSU reviewed the draft report and made final corrections.

ORGANIZATION OF THE REPORT

The report presentation is organized into the five general areas in the scope of work. The first portion of the report concentrates on defining the characteristics and quantities of solids and sediment materials which come from treatment plant and combined sewer overflows. Consideration is given to the possible interaction of these materials with the receiving water environment. The second portion of the report deals with existing technology for modeling sediment movement. Emphasis is placed on the application of this technology to the prediction of the fate of sewer-related sediments. Sediment transport routines from a watershed sediment model developed at Colorado State University were combined with a finite difference flow model of the Cuyahoga River below the Akron, Ohio, sewage treatment plant as described in the study organization. The results of these tests are used to define the usefulness of current modeling knowledge. Weaknesses in the model are identified and areas for further research are defined. The final portion of the report deals with related aspects of sediment studies. These include sampling and analysis procedures plus a short discussion of sediment tracer studies.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

The conclusions from this study fall into five general areas. These concern the characteristics of CSO sediments, the interaction of the sediments with the receiving waters, the interaction of the sediments and the biologic community, modeling of sediment movement, and sampling and tracing of sediments. These areas correspond in general to elements of the scope of work. The general findings and conclusions from each of the five areas are described below. The general recommendations made as a result of the study are presented last.

FINDINGS AND CONCLUSIONS

Knowledge of the Characteristics of CSO Sediments

Characterizing CSO sediments was a major work element. It was found that considerable information is available concerning the nature of the sediment material from CSO's. In general, this information has been collected near major urban areas such as San Francisco, Washington, D.C., or Philadelphia as part of site-specific studies, Ample evidence exists to show the undesirable nature of CSO sediments. Pollutants ranging from lead and mercury to pesticides may be found. In terms of modeling sediment movement, the literature is sparce on useful data. The data suggest that during times of storm flow the urban surface runoff is the major contribution to CSO flow. Thus surface runoff sediments are a major portion of CSO sediments. Street surface solids comprise the major portion of urban surface runoff. These solids range from .063 to 2 or 3 mm in diameter with the distribution of sizes roughly normal. The median diameter varies with geographic location. It would be highly desirable to obtain further information on both the size distribution and settling characteristics of the solids from CSO's. Such information should be routinely gathered as part of any site-specific CSO sediment model study.

Only general conclusions can be drawn regarding the characteristics of CSO sediments. The approximate concentrations and the general size and composition are known. Specifically lacking for modeling purposes are:

--detailed information on the size distribution and settling characteristics of the sediments over the course of a storm event;

- --general information on the geographic differences on the size distribution and settling characteristics of CSO sediments; and
- --additional information concerning the variety and nature of pollutants associated with sediments.

Studies to obtain some or all of the above at a variety of geographic locations would be desirable.

Interaction Between Sediment Materials and Receiving Waters

The literature search resulted in almost no information concerning the chemical interaction of CSO sediments either with themselves or the receiving water. Chemical reactions may change the sediment transport characteristics of CSO sediments, particularly the particle size and weight. The magnitude of such changes and their effect on predictions of sediment models is unknown.

Because of the complexity and number of possible reactions, it is doubtful that a meaningful sediment model, including chemical reactions, could be developed on purely theoretical grounds. A highly useful area of research would be to conduct size distribution and settling tests on actual CSO sediment materials. These tests should include time variation in settling (say two weeks to one month) and settling in different native waters (different pH, alkalinity, etc.). Such tests would establish the variation in settling properties and provide reasonable grounds for adjusting models to account for these factors.

Interaction Between Sediments and the Biologic Community

Volumes of information are available concerning the variety of plant and animal life which live in receiving waters. With the exception of fish spawning beds, little has been done to determine the effects of sediment on the biologic community. A number of general statements can be found regarding turbidity and reduction of light to plants. It is certain that sediment deposits cause biologic communities to move from one area of a stream to another. Certain plant species may be killed by burial or conversely fertilized by shallow deposits. A major interdisciplinary study would be required to determine the effects for any specific stream reach. Some general information could be obtained by investigating the sensitivity or depth of burial. Such investigations might prove useful at a later time when the ability to predict sediment deposit areas and rates has been firmly established. At this time, further study of the biologic community is not warranted.

Modeling the Movement of CSO Sediments

The feasibility of modeling the movement of CSO sediments was investigated on a 64.37 (40 mile) reach of the Cuyahoga River between Akron and Cleveland, Ohio. The reach investigated was quite steep (slope = .00095). Two small diversion structures formed sediment trap areas. The downstream end of the reach included the Cuyahoga estuary into Lake Erie.

The sediment transport routines from a watershed model developed at CSU were combined with a linear implicit finite difference flow model for use in the model study. Limited field data were gathered on sediment sizes and stream cross sections. Flow and suspended sediment data were obtained from the U.S. Geological Survey. Inflows to the study reach from the Akron treatment plant high flow bypass (a CSO) were estimated using data from CSU's literature search.

Experiments indicate that the movement of the hypothetical CSO sediment loads could be successfully modeled. Under normal summer low flow conditions, sediment accumulates near the outfall. A flood of five-year recurrence interval will move coarse sediments from the outfall to the trap areas. Fine material moves through the reach and settles in the estuary under all flow conditions.

It was concluded from the model experiments that qualitative and perhaps quantitative predictions can be made concerning the fate of CSO sediments. Qualitative evaluation will require that the model be verified on data collected for that purpose. Particularly important for a verification study will be site specific values of size distributions and settling characteristics of CSO materials.

Several experiments were conducted with hypothetical sediments with specific gravities similar to elemental heavy metals. Qualitative predictions concerning the movement of these materials is also possible. In the study reach used here, heavy materials settled out at the outfall and were moved downstream by a five-year flood.

The lack of site specific information at the Akron bypass prevented accurate verification in this study. The model currently available will work for materials with variable specific gravities and sizes ranging from silt to gravel. Currently, the model is in two separable pieces, flow and sediment transport. Modifications may be required for directly coupling the flow portion of the model to the sediment transport portion if large changes in bed elevation (10 cm or so) occur in the channel bed. Such large changes would change the water surface profile and transport velocities thus requiring the direct coupling.

The current model considers all sediments to be noncohesive. This generally limits the applicability to particles silt size and larger (generally, .063 mm or larger). Enough data are available in the literature to extend the model to noncohesive clays. The model is primarily limited by the amount and quantity of input data. Particularly important for sediment studies are settling velocity data from the particular outfall or outfalls in question, accurate data concerning the longitudinal slope of the channel bed, and the characteristics of the bed and suspended sediments.

Sampling and Tracing Techniques

A sizable body of literature exists concerning sampling and tracing of sediments. Suspended sediment can be sampled with a fair degree of accuracy using standard samplers developed by government agencies such as the U.S. Geological Survey (USGS) and U.S. Agricultural Research Service (ARS). Standard samplers are also available for sampling bed and bank material. It is not possible at the time of this writing to determine the quantity of sediment which rolls, slides or bounces along the stream (the bed load). It is necessary to find stream reaches where all the sediment is carried in suspension for accurate measurement. The most useful analysis techniques for investigators contemplating model studies are sieving and settling tests using the visual accumulation tube. The former is widely used to determine size distributions. The latter is used to determine fall velocity of particles. Both are important to model work. Radioactive tracers are the most effective but least environmentally acceptable. Fluorescent dyed particles of sand size could probably be used to trace CSO sediments. Results are highly site specific and qualitative in nature. Considerable sampling and analysis costs are involved with the fluorescent dye tracers.

RECOMMENDATIONS

The most important general conclusion from the above section is that the movement of CSO sediments may be successfully modeled. However, the Cuyahoga River study was not an accurate verification of the model used here. The following recommendations are designed to provide sufficient information to make models quantitatively useful and broaden their range of application:

--First, it is recommended that a study site be selected and sufficient information gathered to accurately verify the model developed in this study. This information should include:

- water discharge into and out of the reach;
- instream sediment discharge into and out of reach;
- water and solids discharge from CSO outfall or outfalls;
- accurate time of travel study;
- identification of key deposition and erosion zones;
- monitoring of bed elevation at the above key zones; and
- samples of stream bed, bank, instream, and CSO sediments.

If possible, the verification study should be conducted in conjunction with a study of other water quality parameters to help establish the correlation of their behavior with sediment movement.

--Second, it is recommended that as part of the above verification study that steps be taken to provide empirical information concerning the interaction between the receiving water and the CSO solids. Information should be gathered on both the changes in transport characteristics as a function of time, and on the effect of the solids on the biologic community. The following activities would be particularly useful:

- Collect large samples of CSO solids over the course of a storm event. Divide the sample into several portions and analyze for size distribution and settling characteristics as a function of time (that is, analyze one of the split samples every 2 or 3 days). The results would help identify changes in transport characteristics in deposits.

-Collect samples of CSO solids and determine their settling characteristics in a variety of receiving water environments. This could be done by using a standard visual accumulation tube and varying the pH, alkalinity, temperature, salinity, and other qualities of the fluid in the column. Such information would help establish the range of error due to such effects.

-As part of the verification study, monitor the biologic community at the sediment ranges. Changes in biota could be correlated with the change in depth and location of deposits. Although such information would be highly site specific, it would aid in establishing the harmful or beneficial effects of CSO sediment deposits.

--Third, it would be worthwhile to investigate qualitatively the movement of CSO sediments under a variety of stream conditions. This could easily be done using the sediment model. The reach of the Cuyahoga investigated in this study was rather steep, and contained several sediment traps. Ranges of slopes from very flat (say equal to the lower Mississippi) to that of the Cuyahoga and with and without traps could be modeled. It would also be desirable to model a variety of bed and bank conditions. The Cuyahoga has a coarse, armored bed; nearly a rigid boundary. Reaches with fine sand beds similar to the CSO material will make it much harder to track sediment movement.

--If the model verification study proves to be successful, final modifications should be made to the model and documentation provided. This would make the technology available to other investigators.

SECTION 3

SEDIMENT CHARACTERISTICS AND POTENTIAL IMPACTS

INTRODUCTION

This section of the report is divided into two subsections. The purpose of the first subsection is to determine from existing studies the characteristics of the sediment material from combined sewer overflows. Emphasis is placed on determining those characteristics most important to sediment modeling. The purpose of the second subsection is to discuss in general the receiving water environment. First, the potential interaction between the receiving water and the sediment material is considered. Next, the biologic community is discussed along with the possible impacts caused by the sediment.

Much of the second subsection is speculative in nature because of an almost complete lack of data. Areas of potential research could be identified but very few hard facts are available. The most factual information is contained in the first subsection. Sufficient information was found to conduct the modeling experiments which are described in Section 4.

CHARACTERISTICS OF CSO SEDIMENT MATERIALS

Approach of This Subsection

The term characteristics, as used in the above heading, means both the physical characteristics such as size and composition as well as the time varying characteristics such as quantity and chemical properties. In order to successfully model the fate and effects of the sediment material from sewer and combined sewer outfalls, it is necessary to have information on both.

No field or laboratory data concerning CSO material were collected as part of this study. A thorough search was made of current literature concerning urban runoff. All relevant information on the physical characteristics, chemical properties, and time variation of sewer related sediment material was gathered. Those portions of this information relevant to modeling are presented below. The data vary widely in quality, but wherever possible, limited generalizations were drawn.

CSO's are composed of sanitary sewage and surface runoff typically from urbanized areas. The relative amounts of these two types of flows will depend on a variety of factors such as the intensity of rainfall and the time of day and year. Because the characteristics of sanitary sewage and urban runoff are quite different, it should be expected that characteristics of CSO's for any particular area would fluctuate markedly. There is a significant body of data characterizing the two types of flows individually and from these data it is possible to infer the composition of CSO's.

The approach taken here will be to characterize sanitary sewage and urban runoff individually and then to extrapolate these characteristics to obtain CSO characteristics as related to physical transport of CSO solids. Because the impact of CSO solids on water quality may be related more to the materials attached to the transported solids, an indication of the types and characteristics of these materials will also be presented. It should be noted that many reactions can occur that will not significantly affect the transport potential. For a complete water quality modeling effort, such reactions would need to be considered. Some of the potential interactions are considered in the next subsection.

General Characteristics

The characteristics of CSO's will vary significantly from location to location and will depend on a variety of factors. Because of this, only approximate descriptions of the characteristics can be presented in a summary of this type. In order to develop a model of a specific area, the data given here should be supplemented.

Sanitary Sewage--

Flows--Sanitary sewage flows vary from location to location and also vary with time. Typical flow characteristics are presented in Figure 1 (5). Two distinct daytime peaks typically occur and the ratio of maximum and minimum flows over the course of a day typically ranges from three to five.

Parameter concentrations--As with flow, sewage strength varies over the course of a day. The fluctuations for many of the constituents are not as pronounced as the fluctuations in flow and average values are useful (although site specific data are essential for characterizing individual locations). Average concentration of selected parameters are listed in Table 1.

Urban Surface Runoff--

Characteristics of urban surface runoff are more difficult to quantify than are those of sanitary sewage. This is due, in large part, to the difficulties encountered in obtaining representative samples. It is also due to the fact that concentrations of the various parameters of interest in urban surface runoff vary markedly with time, and the runoff events are often of short duration. There are two stages in gathering data on urban stormwater characteristics. The first of these is to measure the accumulation and composition of dust, dirt, and other materials on street surfaces. The second method is the end of pipe measurement of flow and pollutant concentration.

The street solids make up one of the portion of the solids in urban runoff and CSO's however, there are other contributions that are not negligible such as: eroded material from pervious areas, solids washed from nonstreet impervious areas, re-entrainment of previously deposited materials (e.g., dry-weather deposition) in the conveyance system, atmospheric washout, and the

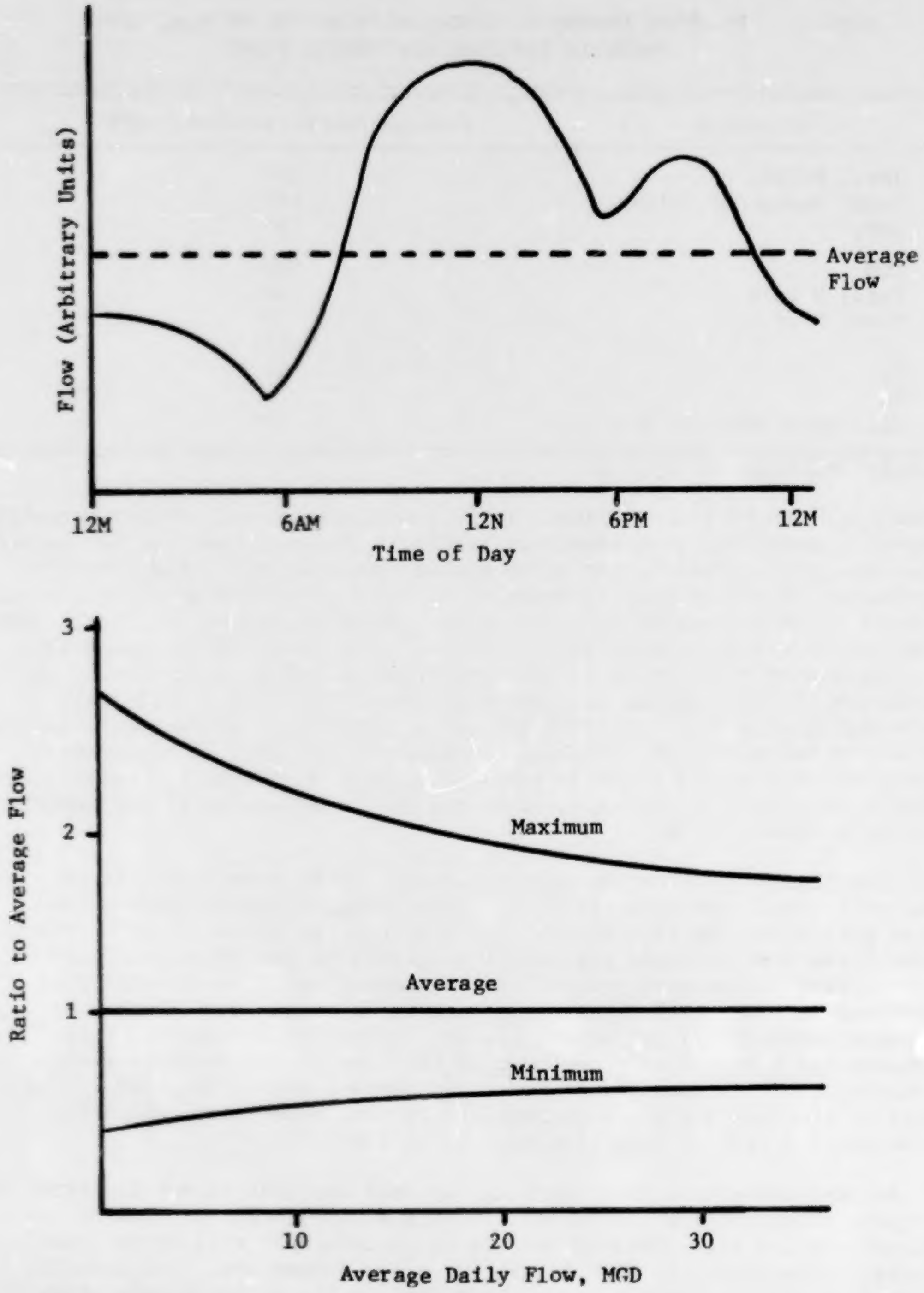

Figure 1. Sanitary Sewage Flow Characteristics [After Metcalf and Eddy, 1972 (5)]

TABLE 1. REPORTED PARAMETER CONCENTRATIONS FOR TYPICAL RAW DOMESTIC SANITARY WASTEWATER FLOWS

Parameter	Average Concentrations, mg/ℓ
Total Solids	860
Total Suspended Solids	160
BOD_5	150
COD	320
Total N as N	30
Total P as P	8
Cl^-	50
Pb	34
Zn	7
Coliforms (MPN/100 ml)	10^6

Source: Manning, et al., (6)

sanitary portion of the overflow. Furthermore, the street sampled material (removed by sweeping, vacuuming, or flushing techniques) may not be related in the same proportions by the storm washoff process (i.e., the particles distribution of street sampled material is not necessarily equal to the distribution of street solids in the runoff). In other words, the street solids assumption is not that great for urban runoff let alone CSO's, Ammon (7). While the end of pipe method is the most representative of the actual characteristics of CSO's during a given storm event, the data is difficult to obtain and is also site specific; therefore, the street surface data is often more useful for predictive modeling, Berwick et al., (8). A qualitative description of a runoff event in terms of flow rate, parameter concentration in the surface runoff, and total parameter load transmitted by the runoff is given in Figure 2, Amy et al., (9).

From Figure 2, it can be seen that each of the quantities plotted varies with time. The hydrograph, or "flow" line, reaches a peak value at some time after the flow begins. This is related to the "time of concentration," the time required for runoff generated in the drainage areas to reach the flow measurement point. The concentrations of many parameters of interest decrease with time, a phenomenon that has been indicated by many researchers and is referred to as the "first-flush" effect. This phenomenon may become less pronounced as the size of the drainage basin and intricacy of interconnecting sewers increases, Wanielista, (10). The product of the flow and the concentration is the "mass rate," which is seen to reach a peak at some time after runoff occurs.

Another phenomenon that has been reported and that is not indicated on the figure is variability in characteristics as a function of time of year. Kleusener and Lee (11) observed this to be particularly true in the case of certain nutrients. It may be true for other parameters. For example, suspended solids concentrations may be higher in the spring before grass is established than in the summer.

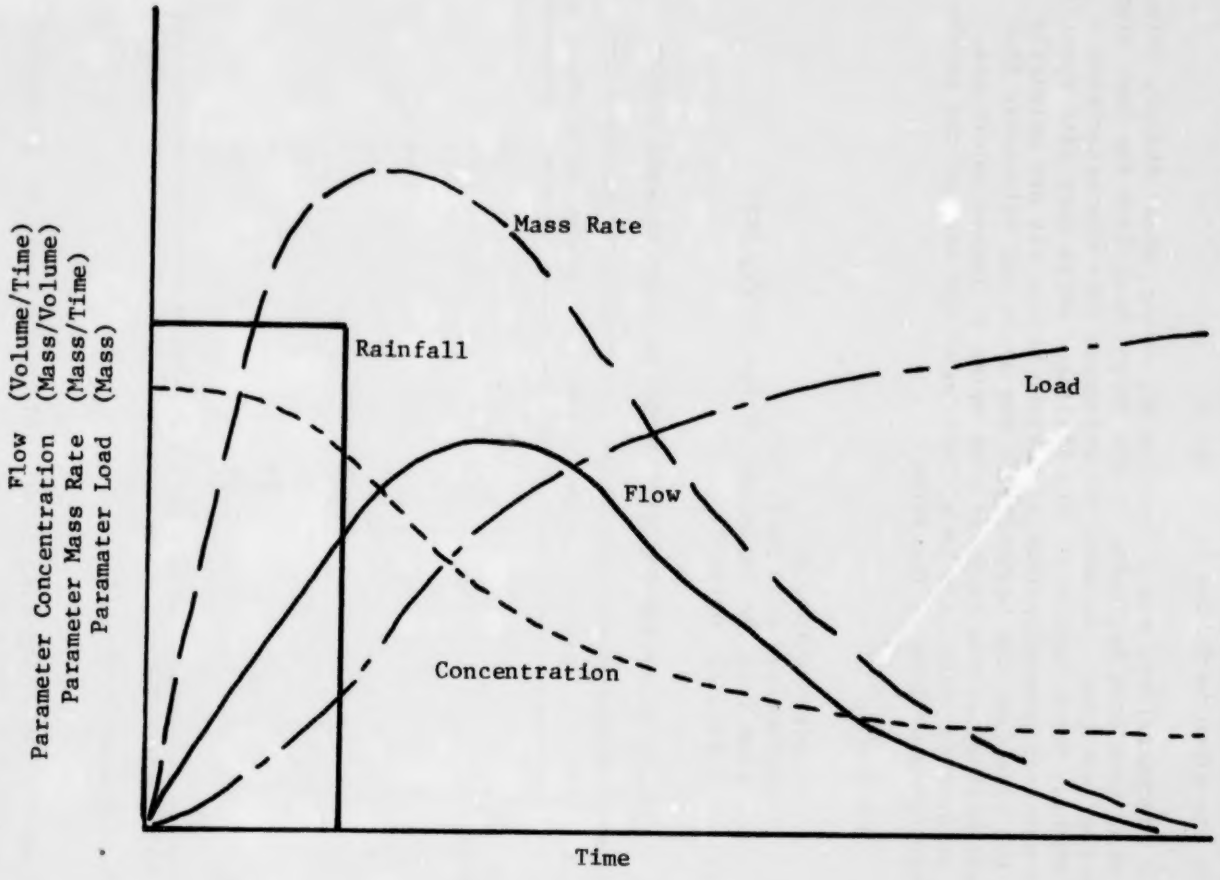

Figure 2. Qualitative Description of an Urban Surface Runoff Event (Wanielista, 10)

As can be seen from Figure 2, average parameter concentrations for surface runoff, as are often reported, are probably not very meaningful. However, average values are derived from analyses of samples collected during runoff events and as such may give some indication of the types and concentrations of parameters that may be found. Typical values for concentrations in urban surface runoff are given in Tables 2, 3, and 4.

Parameter concentrations are a function of, among other things, volumetric flow rate, time from beginning of the storm, time from the last storm, and time from the last peak. Colston (1) presented data characterizing a watershed in Durham, North Carolina. His findings, while very site specific, indicate that observed concentrations of various parameters are primarily functions of the time from the beginning of the storm and volumetric flow rate, with past history of the drainage area being of lesser importance. However, the volumetric flow rate is a function of the size of the catchment. He presented equations of the form:

$$C = b\, Q^m\, t^n$$

Where:

C = concentration, mg/ℓ
Q = volumetric flow rate, cfs
t = time from the beginning of the storm, hrs
b, m, n = empirical constants

TABLE 2. TYPICAL PARAMETER CONCENTRATIONS IN URBAN SURFACE RUNOFF

Parameter	Concentration, mg/ℓ*	Number of Studies, n
Total Solids	496	20
Suspended Solids	210	20
BOD_5	14	28
COD	87	25
TOC	31	15
NO_3-N	0.50	4
TKN	0.72	16
NH_3-N	0.39	4
Ortho PO_4-P	0.25	19
Cl^-	9	15

*Geometric mean of n studies

Data Source: Manning et al., (6)

Empirical values for the constants, determined on the basis of 36 sampled storms, are presented in Table 5.

TABLE 3. OBSERVED RUNOFF WATER QUALITY CONCENTRATIONS IN URBAN STREET RUNOFF IN SAN JOSE, CALIFORNIA

Parameter, Units*	Number of Analyses	Minimum	Maximum	Average
Common Parameters and Major Ions				
pH, pH units	88	6.0	7.6	6.7
Oxidation Reduction Potential, mV	39	40	150	120
Temperature, °C	11	14	17	16
Calcium	5	2.8	19	13
Magnesium	5	1.4	6.2	4.0
Sodium	5	<0.002	0.04	0.01
Potassium	5	1.5	3.5	2.7
Bicarbonate	5	<1	150	54
Carbonate	5	<0.001	0.005	0.019
Sulfate	5	6.3	27	18
Chloride	5	3.9	18	12
Solids				
Total Solids	20	110	450	310
Total Dissolved Solids	20	22	376	150
Suspended Solids	20	15	845	240
Volatile Suspended Solids	10	5	200	38
Turbidity, NTU**	88	4.8	130	49
Specific Conductance, μmhos/cm	88	20	660	160
Oxygen and Oxygen Demanding Parameters				
Dissolved Oxygen	11	5.4	13	8.0
Biochemical Oxygen (5-day)	13	17	30	24
Chemical Oxygen Demand	13	53	520	200
Nutrients				
Kjeldahl Nitrogen	13	2	25	7
Nitrate	5	0.3	1.5	0.7
Orthophosphate	13	0.2	18	2.4
Total Organic Carbon	5	19	290	110
Heavy Metals				
Lead	11	0.10	1.5	0.4
Zinc	11	0.06	0.55	0.18
Copper	11	0.01	0.09	0.03
Chromium	11	0.005	0.04	0.02
Cadmium	11	<0.002	0.006	<0.002
Mercury	11	<0.0001	0.0006	<0.0001

*mg/ℓ unless otherwise noted
**Nephelometric turbidity units

Source: Pitt (12)

TABLE 4. AVERAGE NATION-WIDE POLLUTANT STRENGTHS ASSOCIATED WITH STREET SURFACE PARTICULATES

Parameter (ppm^3 except as noted)	Mean Strength	Minimum Strength	Maximum Strength	Standard Deviation	Ratio of Standard Deviation to Mean
BOD_5 (b)	70,000^e	8,500^e	270,000^e	80,000^e	1.1
COD (b)	140,000	17,000	530,000	160,000	1.1
Ortho PO_4 (b)	1,300	14	6,700	1,400	1.1
Total PO_4 (b)	2,900	210	5,400	f	-
NO_3 (b)	800	20	16,000	2,600	3.3
NO_4 (b)	2,600	600	5,400	f	-
Kjeldahl N (b)	3,000	450	13,000	3,100	1.0
Cd (b)	3.4	0	25	3.6	1.1
Cr (b)	210	3	760	110	0.52
Cu (b)	100	8	290	100	1.0
Fe (b)	22,000	2,200	72,000	11,000	0.50
Pb (b)	1,800	0	10,000	2,000	1.1
Mn (b)	420	100	1,600	220	0.52
Ni (b)	35	0	170	38	1.1
Sr (b)	21	0	110	21	1.0
Zn (b)	370	21	1,100	210	0.57
Total coliforms [no/gm] (d)	2.5×10^6	1.2×10^4	8.6×10^7	g	-
Fecal coliforms [no/gm] (d)	1.7×10^5	6.0	1.7×10^7	g	-
Asbestos [fibers/gm] (c)	160,000	0	770,000	180,000	1.1
Rubber (c)	4,600	500	11,000	2,600	0.57
p, p-DDD (d)	0.082	0.0002	0.27	0.080	0.98
p, p-DDT (d)	0.075	0.0004	0.38	0.12	1.6
Dieldrin (d)	0.028	0.003	0.074	0.028	1.0
Endrin (d)	0.00028	0	0.0022	0.00073	2.6
Lindane (d)	0.0022	0	0.019	0.0063	2.9
Methoxychlor (d)	0.50	0	3.1	1.1	2.2
Methyl parathion (d)	0.0024	0	0.022	0.0073	3.0
PCB's (d)	0.77	0.07	2.3	0.76	1.0

TABLE 4. AVERAGE NATION-WIDE POLLUTANT STRENGTHS ASSOCIATED WITH STREET SURFACE PARTICULATES (Continued)

(a) ppm = microgram of pollutant per gram of total dry solids; the mean total solids (b) accumulation was 150 lb/curb-mile/day, with a range of 3 to 2,700 and a standard deviation of 370 lb/curb-mile/day.

(b) Amy et al., (9) - a compilation of the results of many studies

(c) Shaheen (13)

(d) Sartor and Boyd (14)

(e) BOD = ½ COD [See Colston, (1)]

(f) Few samples (less than 10)

(g) Very large variance.

Source: Pitt (12)

TABLE 5. EMPIRICAL CONSTANTS FOR THE EQUATION

$$C_{(mg/\ell)} = b\ Q^{m}_{(cfs)}\ t^{n}_{(hrs)}$$

FOR PARAMETER CONCENTRATION IN URBAN SURFACE RUNOFF FOR FOR THIRD FORK CATCHMENT, DURHAM, NORTH CAROLINA

Parameter	b	m	n
COD	113	0.11	-0.28
TOC	32	0.0	-0.28
TS	420	0.14	-0.18
TVS	130	0.09	-0.11
TSS	222	0.23	-0.16
VSS	44	0.18	-0.17
TKN	0.85	0.87	-0.29
Total P	0.80	0.03	-0.29
Al	10	0.05	-0.15
Ca	12.5	-0.4	-0.09
Co	0.07	0.18	+0.13
Cr	0.18	-0.04	+0.06
Cu	0.08	0.10	+0.09
Fe	4.6	0.24	-0.18
Pb	0.27	0.125	-0.29
Mg	10.0	-0.02	-0.16
Mn	0.45	0.11	-0.27
Ni	0.12	0.03	-0.01
Zn	0.22	0.10	-0.22

Source: Colston (1)

Colston's results (1) indicate that for nearly all of the parameters studied a peak concentration occurs during the initial "rising leg" of the hydrograph. This peak typically occurs at the beginning of the storm, although for several of the parameters studied, there is an initial increase in concentration with time followed by a decrease. Such a peak corresponds to the first-flush effect referred to earlier. The magnitude of the effect appears to vary among parameters.

Work was completed recently by Huber et al., (15) for the actual stormwater quality data for CSO's for 35 storms and eight locations. Some of the data was evaluated by statistical analysis for BOD_5 and suspended solids. While this work is still in its preliminary stages, future regression analysis work on the presented data will attempt to find the causative relationships among the water quality parameters and hydrologic and demographic factors. A summary of the water quality characteristics for the flow-weighted BOD_5 and suspended solids data by land use and type of sewerage is presented in Table 6.

TABLE 6. COMPARISON OF FLOW-WEIGHTED BOD$_5$ AND SUSPENDED SOLIDS MEANS AND STANDARD DEVIATIONS BY LAND USE AND TYPE OF SEWERAGE

City-Catchment	Storm or Combined Sewerage	00310[a] BOD$_5$		Number of Events	00530[a] Susp. Solids		Number of Events
		Mean (mg/ℓ)	Std. Dev. (mg/ℓ)		Mean (mg/ℓ)	Std. Dev. (mg/ℓ)	
Single-Family Residential							
San Francisco, CA-Selby St.	C	38.1	30.0	8	215.4	146.0	8
Racine, WI-Site I	C	89.1	17.7	7	178.9	137.3	7
Lancaster, PA-Stevens Ave.	C	56.2	49.3	5	271.3	171.1	5
Broward County, FL-Residential	S	6.7	4.3	20	28.4[b]	16.7[b]	28
San Francisco, CA-Vicente St. N.	S	9.8	11.4[c]	1	48.3	29.2[c]	1
San Francisco, CA-Vicente St. S.	S	4.5	3.4[c]	1	45.8	29.3[c]	1
Lincoln, NE-39 and Holdrege	S	37.6	51.8	13	735.9	302.8	18
Lincoln, NE-63 and Holdrege	S	22.1	32.5	11	827.7	228.4	12
Lincoln, NE-78 and A	S	8.7	5.1	9	1,532.0	780.4	10
Windsor, OR-Labadie Road	S	16.9	8.2	20	389.8	254.2	20
Seattle, WA-View Ridge 1	S	18.4	11.2	7	55.6	102.5	28
Seattle, WA-View Ridge 2	S	12.9	9.4	5	107.7	33.1	4
Seattle, WA-Lake Hills	S	6.3	2.9	5	61.3	9.9	5
Seattle, WA-Highlands	S	4.2	3.8	4	109.3	71.5	4
West Lafayette, IN-Ross-Ade	S	59.6	89.7	8	104.7	52.0	8
Greenfield, MA-Maple Brook	S	11.6	7.2	4	147.4	112.1	5
Multiple-Family Residential							
San Francisco, CA-Baker St.	C	22.9	6.0	3	90.7	14.5	3
San Francisco, CA-Brotherhood Wy	C	45.6	24.7	3	654.8	524.6	3
San Francisco, CA-Laguna St.	C	46.3	8.8	2	210.7	101.0	2
Commercial							
Seattle, WA-Central Bus. Dist.	C	64.3	37.7	5	161.8	21.7	5
Seattle, WA-Southcenter	S	12.5	7.7	7	93.5	237.0	27

TABLE 6. COMPARISON OF FLOW-WEIGHTED BOD_5 AND SUSPENDED SOLIDS MEANS AND STANDARD DEVIATIONS BY LAND USE AND TYPE OF SEWERAGE (Continued)

City-Catchment	Storm of Combined Sewerage	00310[a] BOD_5		Number of Events	00530[a] Susp. Solids		Number of Events
		Mean (mg/ℓ)	Std. Dev. (mg/ℓ)		Mean (mg/ℓ)	Std. Dev. (mg/ℓ)	
Industrial							
Seattle, WA-South Seattle	S	11.9	8.2	7	114.2	176.3	29
Mixture-Res., Com., Other							
San Francisco, CA-Mariposa St.	C	43.2	42.5	3	172.4	86.4	3
Durham, NC-Third Fork	S	127.3	13.6	2	1,498.3	171.2	4
Northampton, MA-Market St. Brook	S	30.1	19.4	3	149.2	55.0	6

(a) STORET code for parameter

(b) Parameter 70299 reported instead of 00530, i.e., suspended solids determined by evaporation instead of filtration.

(c) Standard deviation based on within-storm variation, 8 samples for BOD_5 and 10 samples for SS.

Source: Huber et al., (15)

Summary--

Typical data for sanitary sewage, urban surface runoff, and combined sewer overflows are presented in Table 7. This table gives an indication of the qualitative effects of combining sanitary sewage with urban surface runoff. The differences noted between these values and those reported in the previous tables support the need for future work to determine which factors affect the water quality.

TABLE 7. TYPICAL PARAMETER CONCENTRATIONS FOR SANITARY SEWAGE, URBAN SURFACE RUNOFF, AND COMBINED SEWER OVERFLOWS

Parameter	Concentration, mg/ℓ		
	Sanitary Sewage	Urban Surface Runoff	Combined Overflows
TS	700	496	589
TSS	200	415	370
BOD_5	200	20	115
COD	500	115	375
Total N	40	3 to 10	9 to 10
Orthor PO_4 as P	7	0.6	1.9

Source: Manning et al., (6)
Metcalf and Eddy (5)

It is readily apparent that the characteristics of CSO's will be dependent on the relative volumes of urban surface runoff and sanitary sewage. These, in turn, will depend on the variety of factors including time of day, intensity of rainfall, time since the beginning of the rainstorm, and time of year among others.

What can be noted from Table 7 is that sanitary sewage can be expected to significantly influence the concentrations of most of the parameters. The important exception, which is notable in light of the purpose of this report, is suspended solids. The suspended solids concentrations for sanitary sewage and urban surface runoff are roughly equivalent so if urban surface runoff contributes the majority of the volume of a CSO, as would typically be the case, the suspended solids characteristics of the CSO would be expected to be similar to those of the urban surface runoff.

Characteristics Related to Transport

Because CSO's can affect water quality in receiving waters, movements of CSO's are important. The water quality effects observed will be dependent on both the location of the CSO material at any time and the characteristics of the material that affect water quality. The present study focuses on movement of CSO solids.

Sanitary Sewage--

The contributions of solids by sanitary sewage may be small and these solids will probably have a minor effect on the outfall characteristics of CSO solids. Little research effort, however, has been directed towards quantifying the relative significance of sanitary sewage and urban surface runoff on CSO's.

Time dependent changes in the physical charactertistics of CSO solids may be significantly affected by sanitary sewage. For instance, sanitary sewage will play an important role in any reactions involving nutrients that lead to changes in the physical characteristics of the CSO solids. The effects of these reactions might be completely different if only urban surface runoff were involved.

Combined sewer systems are generally designed to handle the peak sanitary sewage flow plus a part of the urban runoff flow. A common basis for design is to provide for a maximum flow of two to four times the average dry weather flow. This provides a margin of safety for the anticipated peak sanitary sewage flow. On the average, therefore, overflow from a combined sewer will occur only when the urban runoff is from one to three times the sanitary sewage flow. Significant overflow, on the average, will occur only for urban runoff volumes greater than these values. It is assumed for this study that CSO's consist of primarily urban surface runoff.

Urban Surface Runoff--

Urban surface runoff accounts for the bulk of the solids in CSO's. (Although concentrations are roughly equal, the surface runoff is much greater in volume.) Colston (1) found that for one urban watershed, urban surface runoff accounted for ninety-five percent of the total annual suspended solids loading on the receiving water. Randall et al., (16) obtained a similar result for a larger watershed comprised mainly of urbanized areas. Because such a large percentage of the suspended solids load is contributed by urban surface runoff, the characteristics of the solids in CSO's might be expected to be similar to those of urban surface runoff alone.

In modeling the transport of CSO solids, two basic classes of processes must be considered. First, transport depends on the quiescent settling characteristics of the solids. Second, any time dependent changes in the settling characteristics, mass rate, or other transport variables must be included in the analysis. These two classes of processes are discussed in the following sections.

Reported Settling Data--In terms of quantifying the physical characteristics that relate to transport, the most direct method may be to measure settling velocities under quiescent conditions. Unfortunately, data of this type are limited. Dalrymple et al., (17) presented settling data for both stormwater runoff and sanitary sewage, and these data are reproduced in Figure 3. For the samples tested, the stormwater solids settled more slowly

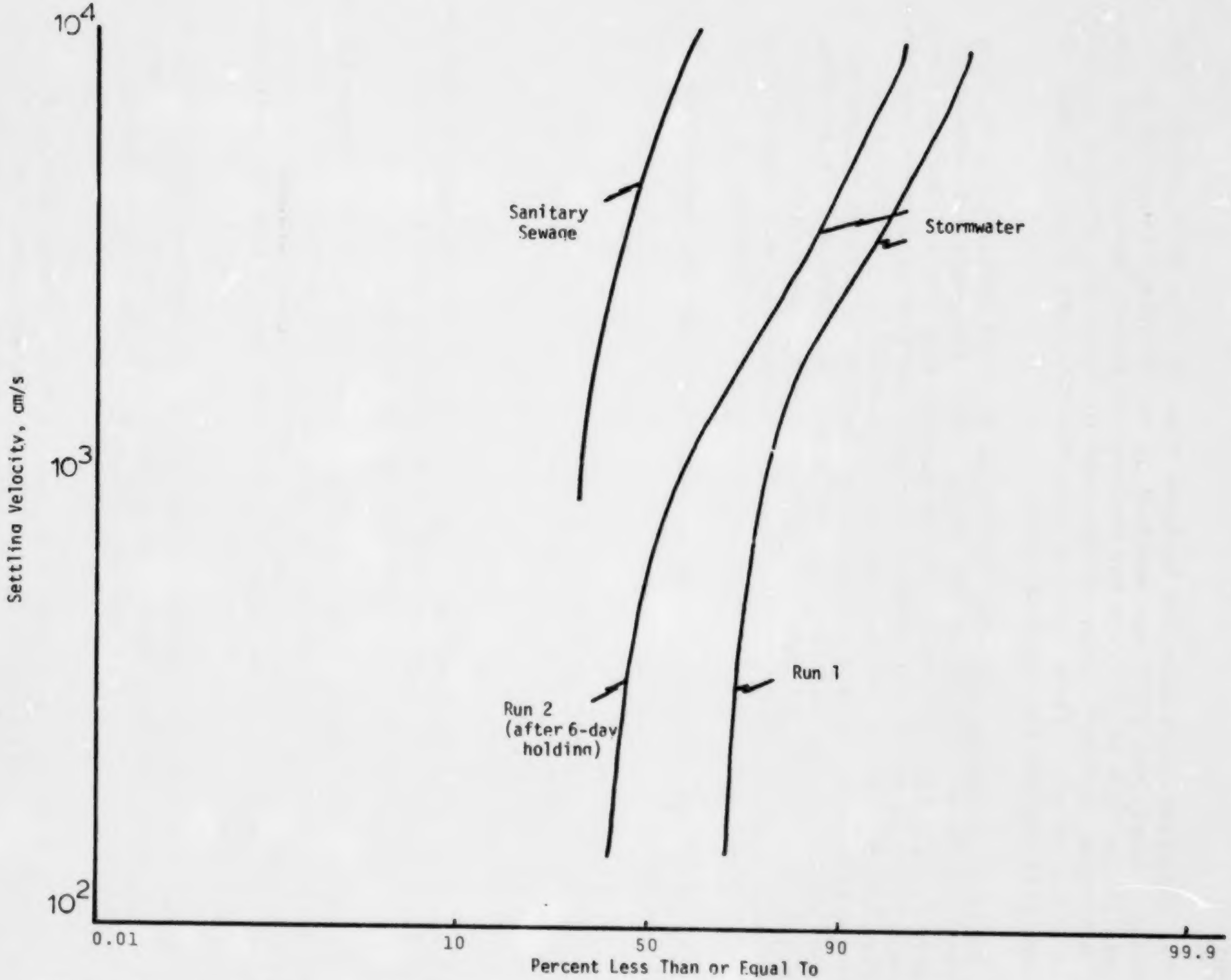

Figure 3. Settling Data for Stormwater Runoff and Sanitary Sewage; Dalrymple (12)

than the sanitary sewage solids. No information was presented characterizing the drainage basin or indicating the condition under which the samples were collected. Therefore, the data are probably not representative of CSO's in general.

One important conclusion can be drawn from the data of Figure 3. The stormwater sample was split and analyzed at two different times and an increase in the rate of settling was observed following "aging" of the sample. Apparently time dependent processes occurred to change the physical characteristics of the sample. These types of proceses will very likely be important in characterizing the transport of CSO's.

Generated settling data--Few definitive data are available describing the settling characteristics of CSO solids. This information is essential for developing a transport model for the materials in CSO's. Obviously one approach could be to collect samples from each overflow of interest and characterize the material in the laboratory. This would be a difficult and expensive procedure. A second alternative would be to attempt to generate settling data from the data that are available. An approach to generating the required data will be presented in this section, along with an outline of research needs to develop a procedure for estimating the characteristics of CSO's without extensive field work for locations of interest.

The variables affecting quiescent settling of discrete nonreactive particles are:

--particle size,
--particle specific gravity,
--particle shape,
--fluid density, and
--fluid viscosity.

These types of data are available from a variety of sources and from them it is possible to generate data that may be at least representative of the types of characteristics to be expected for CSO solids.

Particle size data have been obtained in several studies. Solids in urban surface runoff originate mainly from impervious surfaces (9). Because of the inherent difficulties in obtaining representative samples of CSO's, a number of researchers have taken street surface sample data to be representative of CSO's.

Sartor and Boyd (14) presented data for street surface samples from five cities. Averages of these values are presented in Table 8. Similar data are presented in Table 9 for Chicago (15) and in Table 10 for Washington, D.C. (13).

Dalrymple et al., (17) presented results from previous studies for particle size distributions in CSO's. These data are summarized in Tables 11 and 12. It should be noted that the data of Table 11 were for solids retained in a catch basin from which some particles especially those in the smaller size fractions and less dense, could be lost.

TABLE 8. PARTICLE SIZE DISTRIBUTIONS FOR URBAN STREET SURFACE PARTICULATES

Size Range	Percent Distribution by Weight
>4,800 microns	5.9
2,000 to 4,800	15.7
840 to 2,000	14.0
246 to 840	22.2
104 to 246	17.6
43 to 104	11.0
30 to 43	7.3
14 to 30	3.8
4 to 14	2.1
<4	0.4

Source: Sartor and Boyd (14)

TABLE 9. PARTICLE SIZE DISTRIBUTION FOR STREET SOLIDS SAMPLES FROM CHICAGO, ILLINOIS

	Percent Distribution by Weight		
Size Range	Commercial Site	Industrial Site	Average
2,000 microns	5.8	3.4	4.6
1,190 to 2,000	7.8	7.0	7.0
840 to 1,190	5.2	6.4	5.8
590 to 840	6.6	12.8	9.7
840	74.6	70.4	72.5

Source: APWA, 1969 (18); from Manning et al., (6)

The data of Tables 8 through 13 are presented graphically in Figure 4. In constructing this figure, it was assumed that the geometric mean of each size range represented the midpoint of the weight of material within the range. For example, in Table 8, the size fraction 2,000 to 4,800 microns contained 15.7 percent of the sample by weight with 5.9 percent of the sample larger than 4,800 microns. It was then computed that:

$$100 - (15.7/2) - 5.9 = 86.2 \text{ percent}$$

of the sample had sizes smaller than

$$\sqrt{(2,000)\ (4,800)} = 3,100 \text{ microns.}$$

It is useful for reference to later sections of the report that 1 mm = 1,000 microns; thus, 3,100 microns = 3.1 mm.

TABLE 10. PARTICLE SIZE DISTRIBUTION FOR STREET SOLIDS SAMPLES FROM WASHINGTON, D.C.

Size Range	Percent Distribution by Weight				
	Arterial Roadway	Urban Highway	Shopping Center	Commercial Street	Average
1,700 to 3,350 microns	3.2	8.7	1.8	5.5	4.8
850 to 1,700	7.1	9.6	6.3	8.0	7.8
420 to 850	19.4	14.4	19.7	18.6	18.0
250 to 420	25.2	14.3	25.4	23.0	22.0
150 to 250	19.1	12.3	15.4	16.3	15.8
75 to 150	17.6	17.2	16.4	17.0	17.0
45 to 75	7.6	13.4	10.8	10.6	10.7
45	0.6	10.0	4.3	1.0	4.0

Source: Shaheen, (13); from Manning et al., (6)

TABLE 11. PARTICLE SIZE DISTRIBUTION OF SUSPENDED SOLIDS IN CSO's IN LANCASTER, PENNSYLVANIA

Size Range	Percent Distribution by Weight
9,525 microns	1.77
4,760 to 9,525	1.06
2,000 to 4,760	1.40
1,190 to 2,000	1.88
590 to 1,190	3.10
420 to 590	2.78
210 to 420	7.01
149 to 210	5.19
74 to 149	20.10
44 to 74	23.80
44	31.90

Note: These data represent material retained in a catch basin rather than actual CSO's.

Source: Krants and Russell, (19); from Dalrymple et al., (17)

TABLE 12. PARTICLE SIZE DISTRIBUTION OF SUSPENDED SOLIDS IN CSO's IN SAN FRANCISCO, CALIFORNIA

Size Range	Percent Distribution by Weight
3,327 microns	5.1
991 to 3,327	8.8
295 to 991	15.9
74 to 295	21.8
74	48.3

Source: Envirogencies Co., (20); from Dalrymple et al., (17)

TABLE 13. PARTICLE SIZE DISTRIBUTION IN PERCENT OF SUSPENDED SOLIDS IN CSO's in SAN FRANCISCO, CALIFORNIA BY CATCHMENT LOCATION

Catchment Location	>75μ	14-75μ	5-14μ	0.45-5μ
Baker Street	44.6	32.6	17.0	11.8
Mariposa Street	20.0	74.1	3.4	4.0
Brotherhood Way	79.7	8.6	6.1	7.8
Vicente St. North	78.7	11.2	6.4	3.5
Vicente St. South	86.2	7.6	4.8	4.4
	61.9	26.9	7.6	6.4

Source: Huber et al., (15)

Inspection of Figure 4 indicates reasonable correspondence between the size distributions of CSO solids and street surface solids. The data of Tables 8 and 11 more or less bound the distribution curves. It was noted in Table 11 that those data represent solids retained in a catch basin. It is reasonable to expect that some of the smaller sized particles were washed out of the basin. Removing more fines from the sample would shift the distribution curve up to the left. The size distribution of the original CSO solids would probably fall to the right of the curve shown. As an initial estimate, it is reasonable to assume that CSO solids and street surface solids have the same characteristics, at least when the solids are first picked up by the rainfall generated runoff.

Several researchers have presented size distributions for certain materials found in street surface solids. Data from two of these types are presented in

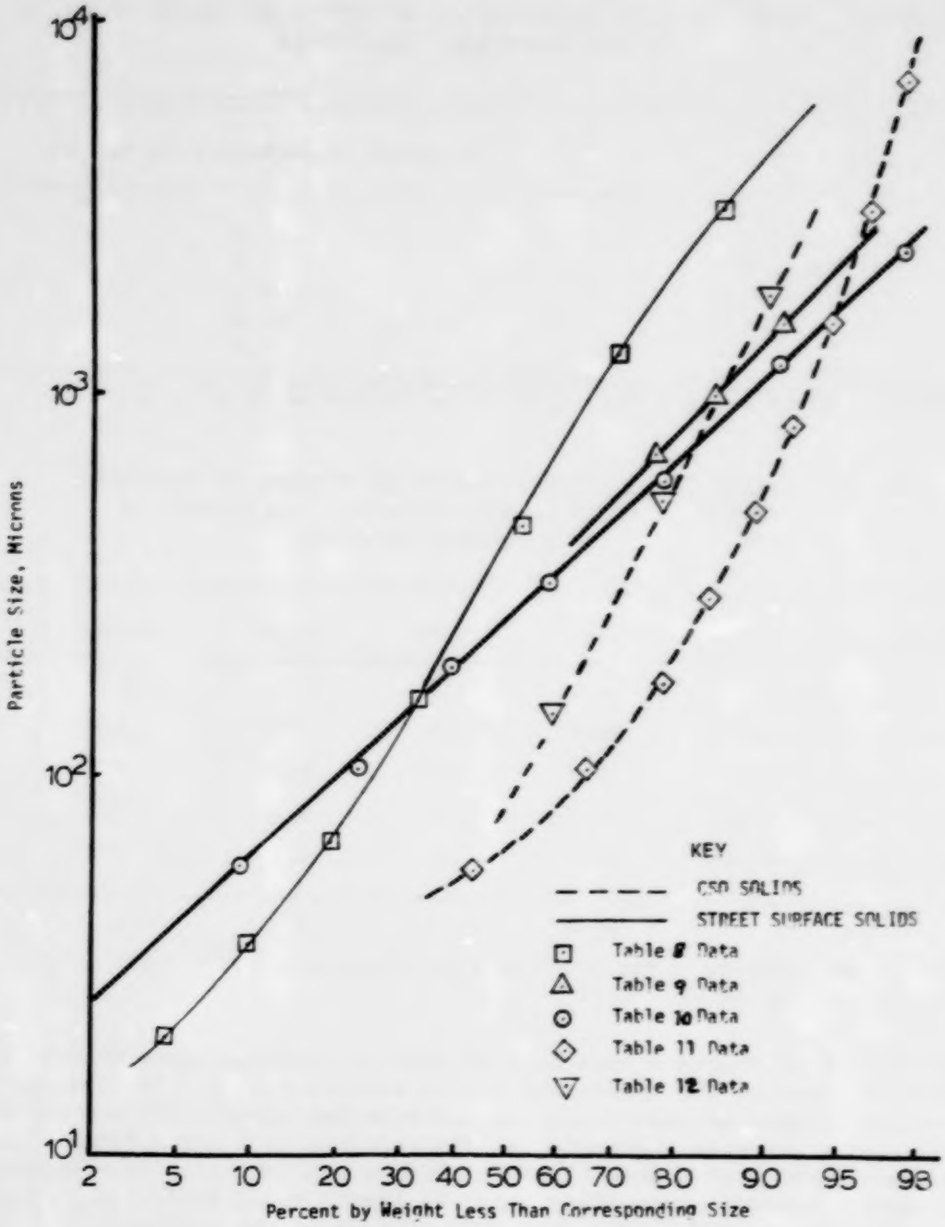

Figure 4. Particle Size Distributions of CSO and Street Surface Solids

Tables 14 and 15. The data for Table 14 were from a large number of cities, while the data for Table 15 were for several types of roadways in Washington, D.C. Selected data from these tables were plotted on probability paper in an attempt to find any trends. Several of the plots are shown in Figure 5. The close agreement with linearity in all cases indicates that the constituents shown, over the size ranges of the available data, have approximately log-normal size distributions. Other constituents from the two data sets were tested in a similar way and in nearly all cases the agreement with linearity was good.

TABLE 14. FRACTION OF CONSTITUENT ASSOCIATED WITH STREET SOLIDS PARTICLE SIZE RANGES

	Particle Size, Microns					
	>2,000	840-2,000	246-840	104-246	43-104	<43
Total Solids	24.4%	7.6	24.6	27.8	9.7	5.9
VS	11.0	17.4	12.0	16.1	17.9	25.6
BOD_5	7.4	20.1	15.7	15.2	17.3	24.3
COD	2.4	2.5	13.0	12.4	45.0	22.7
TKN	9.9	11.6	20.0	20.2	19.6	18.7
NO_3	8.6	6.5	7.9	16.7	28.4	31.9
PO_4	0	0.9	6.9	6.4	29.6	56.2
THM*	16.3	17.5	14.9	23.5	27.8	
T Pesticides	0	16.0	26.5	25.8	31.7	
Cr	26.1	13.6	16.3	16.3	27.7	
Cu	22.5	20.0	16.5	19.0	22.0	
Zn	4.9	25.9	16.0	26.6	26.6	
Ni	26.2	14.2	15.3	17.2	27.1	
Hg	16.4	28.8	16.4	19.2	19.2	
Pb	1.7	2.6	8.7	42.5	44.5	

*Total Heavy Metals
Source: Sarton and Boyd (14)

These observations tend to support the hypothesis that the size distribution of street solids are log-normal distributions. The mean, of course, would be a function of the geographical location. It might also be hypothesized that the size distributions are relatively independent of geographical locations and dependent on such variables as traffic volume and street sweeping schedules. If these hypotheses could be verified, it should then be possible to generate valuable CSO transport data in terms of particle size distributions as a function of the above mentioned variables. These concepts are discussed in more detail in Appendix A.

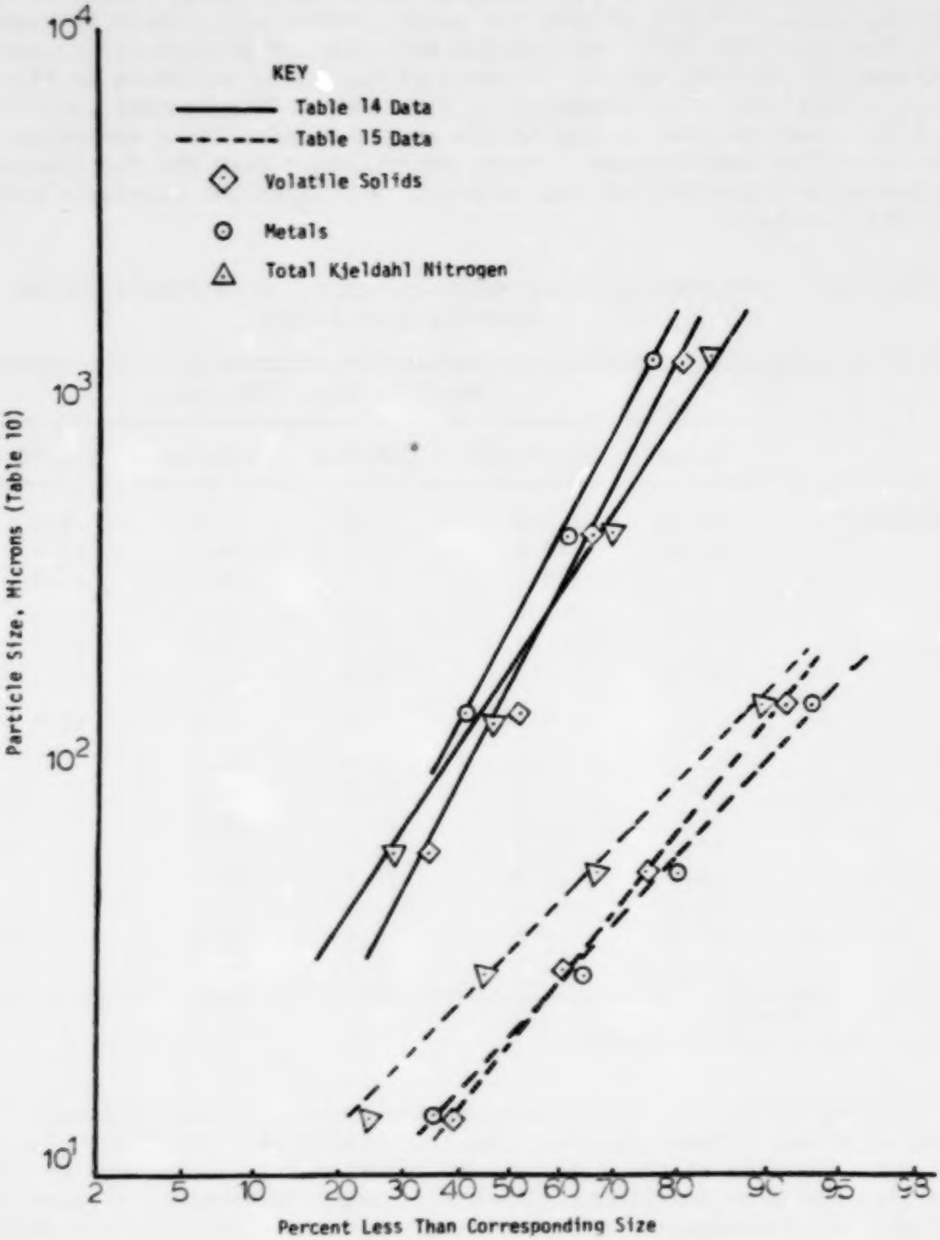

Figure 5. Size Distribution of Selected Constituents of Street Surface Solids

TABLE 15. FRACTION OF CONSTITUENT ASSOCIATED WITH STREET SOLIDS PARTICLE SIZE RANGES (WASHINGTON, D.C.)

	Particle Size, Microns				
	3,350-850	850-420	420-250	250-75	<75
Dust and Dirt	13.6	19.8	23.9	31.3	11.4
Volatile Solids	17.0	14.8	13.1	33.33	21.8
BOD_5	14.7	16.7	20.2	29.4	19.0
COD	12.8	13.4	14.7	36.8	22.3
PO_4 as P	9.4	13.7	19.3	37.9	19.7
NO_3 as N	13.6	13.3	15.7	36.1	21.4
NO_2 as N	24.5	13.6	9.8	21.8	30.3
Total Kjeldahl N	20.1	26.0	17.5	23.9	12.6
Grease	11.6	10.3	12.5	40.1	25.5
Petroleum	10.8	9.1	12.5	39.9	27.7
Asbestos	13.0	15.5	20.5	39.6	11.4
Rubber	3.0	5.4	11.3	37.8	42.5
Pb	6.5	18.3	15.5	42.8	16.9
Cr	16.8	13.2	16.6	36.8	16.6
Ni	25.9	11.8	16.2	29.4	16.7
Zn	7.2	13.9	24.9	40.4	13.6
Cn	8.1	11.7	13.8	44.2	22.2

Source: Shaheen, (13); from Manning et al., (6)

Particle specific gravity depends on the composition of the particle. CSO particles probably tend to change in composition as was indicated by the settling data of Dalrymple et al., (15) presented earlier. Many processes such as agglomeration, adsorption, and biological degradation may occur. These processes are time dependent as well as being functions of variables other than time. As a first approximation, it is assumed that CSO particles are discrete and inert. This assumption is obviously not valid. The amount of error introduced cannot be determined without obtaining additional data. As a first approximation, the assumption is considered reasonable.

Specific gravity data for materials that might be expected to be found in street surface (and thus CSO) samples are given in Table 16. In order to use these data to derive settling data, knowledge of the relative amounts of the various materials is necessary.

Tables 14 and 15 list some of the materials that might be expected to be found in CSO's, but they do not indicate the relative amounts. Manning et al., (6) compiled available data on the loading on street surfaces of many of these types of materials and some of this information is summarized in

TABLE 16. TYPICAL SPECIFIC GRAVITIES OF MATERIAL IN STREET SURFACE SOLIDS

Material	Specifc Gravity	Material	Specific Gravity
Asphalt	1.1 to 1.5	Cr	7.18 to 7.20
Brick	1.4 to 2.2	Cu	8.96
Cardboard	0.69	Fe	7.87
Cement	2.7 to 3.0	Hg	13.55
Clay	1.8 to 2 6	Mn	7.21 to 7.44
Creosote	1.04 to 1.10	Ni	8.90
Glass	2.4 to 2.8	Pb	11.35
Paper	0.7 to 1.15	Zn	7.13
Rubber, hard	1.19		
Silica	2.07 to 2.21		
Tar	1.02		
Wood	0.11 to 1.33		

Source: CRC, (21)

Table 17. Data were collected for a variety of other materials, but the loadings were extremely small in most cases and much less than those listed in all cases. What Table 17 indicates is that the bulk of street surface solids fall into categories other than those listed. A more complete analysis of the makeup of street surface solids is necessary in order to apply the available density data in a reasonable way to predict settling velocities.

TABLE 17. AVERAGE DAILY ACCUMULATION ON ROADWAYS IN MATERIALS IN THE "DUST AND DIRT" FRACTION

Material	Accumulation, kg/curb-km-day
BOD	0.23
COD	2.08
Total N as N	0.02
Total Kjeldahl N	0.03
Cr	0.01
Fe	0.95
Mn	0.02
Pb	0.09
Zn	0.02
Other*	42.00
Total Dust and Dirt	45.0

*Estimated by author

Computed from data summary of Manning et al., (6)

Sources: APWA, (198); Shahee, (13); Sharton and Boyd (14); and Amy et al., (9) In an early study, street surface samples were collected from twenty test sites in Chicago and analyzed for seven classes of materials. A summary of the results is presented in Table 18. In the same study, the specific gravities of street surface samples were determined, and the results of which are given in Table 19. The portion of the street surface material classified in this study consists of particles larger than about 3 mm, and the "dirt" fraction was not based on composition but was made up of the material less than about 3 mm in size.

Data on the composition of the small sized street surface particles that will make up CSO solids are incomplete. It will be assumed, for the purpose of this study, that the makeup of this material is the same as that given in Table 18, neglecting the "dirt" fraction. From the limited data available, this appears reasonable. For example, from Table 17, the accumulation of metals is 2.4 percent of the total which corresponds to the value in Table 18. The actual material composition may be a function of such variables as geographical location and time of year. Development of an empirical relationship to predict the makeup of CSO's would be a valuable contribution. Discussion of this concept is included in Appendix B.

TABLE 18. SUMMARY OF DATA ON COMPONENTS OF STREET LITTER IN CHICAGO, ILLINOIS

Material Class	Percent Distribution by Weight
Rock	10.3
Metal	2.4
Paper	7.6
Dirt	59.6
Vegetation	13.6
Wood	0.5
Glass	1.9
Other	4.1

Computed from data of APWA, (15); from Manning et al., (6)

TABLE 19. SPECIFIC GRAVITY OF "DUST AND DIRT" STREET SURFACE SAMPLES IN CHICAGO, ILLINOIS

Land Use	Specific Gravity Range
Commercial	2.2 to 3.0
Industrial	2.5 to 2.6

Source: APWA (18); from Manning et al., (6)

Taking the data of Table 18 as being representative of CSO's in general, specific gravities of the fractions can be estimated or taken directly from Table 16. Data considered representative of CSO's for the purpose of this study, in terms of composition and density, are given in Table 20. The specific gravity values are estimates and are probably variable. The weighted average specific gravity is less than the values given in Table 19 and a higher value may be more appropriate in some cases.

TABLE 20. PREDICTED DATA FOR COMPOSITION AND SPECIFIC GRAVITY OF CSO'S

Material Class	Percent Distribution by Weight	Specific Gravity
Rock	25.5	2.6
Metal	5.9	8.0
Paper	18.8	1.1
Vegetation	33.7	1.1
Wood	1.2	0.9
Glass	4.7	2.6
Other*	10.2	1.2
	100.0	Weighted Average = 2.0

*Assumed to be rubber

Particle shape is the third particle variable that must be considered in computing settling velocities. Particle shape is used in computing the drag coefficient which is incorporated into a force balance on the particle. A relationship for the drag coefficient on spherical particles has been presented (22) as:

$$C_D = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 \qquad (1)$$

Where:

C_D = drag coefficient

N_R = Reynolds number = $\frac{Vde}{\mu}$

V = fall velocity, ft/sec

ρ = particle density, lb-sec^2/ft^4

d = particle diameter, ft

μ = fluid dynamic viscosity, lb-sec/ft^2

This relationship is reported to be valid to a Reynolds number of about 10^4.

A relationship that appears to fit the experimental data more closely(23) is:

$$C_D = \frac{24}{N_R} + \frac{5}{\sqrt{N_R}} + 0.26 \qquad (2)$$

Experimental data are available for two other idealized shapes, discs, and cylinders. Relationships that fit these data reasonably well are:

$$\text{Discs:}\quad C_D = \frac{24}{N_R} + \frac{5}{\sqrt{N_R}} + 1.14 \qquad (3)$$

$$\text{Cylinders:}\quad C_D = \frac{10}{(N_R)^{0.289}} + \frac{2}{\sqrt{N_R}} + 1.14 \qquad (4)$$

Portions of the CSO particles will fall into each of these classes, and portions will not be described adequately by any of the three idealized shapes. Initially, it is probably reasonable to assume that all the particles are spherical. As data are collected, this assumption may be modified as necessary.

Fluid density and fluid viscosity depend primarily on the temperature of the fluid and the suspended solids load. In most cases it is probably sufficiently accurate to consider these variables to be functions of temperature only. An error in the density value of five percent corresponds to a suspended solids load on the order of 10^5 mg/ℓ, a solution of about ten percent solids. The error in assuming the fluid transporting CSO solids to be pure water will, in most cases, be negligible.

Time can be an important factor in modeling the transport of CSO solids. The effects of time on settling characterisitcs as indicated earlier (17), may be significant. Time may be important is establishing the characteristics of the street surface solids that constitute CSO solids as indicated previously and discussed in the appendices. However, initial estimates for settling characteristics of CSO solids were given in the previous section under the assumption that time dependent changes are negligible.

Storm events that result in the urban surface runoff are time dependent as indicated in the first part of this subsection. The time of year may be important in areas where the frequency and magnitude of rainfall vary seasonally. Also, the type of ground cover on previous surfaces will influence the amount of runoff generated as well as its size distribution and the ground cover varies throughout the year. Time of year and frequency of rainfall, as well as other time related variables will have an effect on the makeup and physical characteristics of CSO solids, as discussed in the appendices. For the purpose of the model study presented in Section 4, all of these time related variables will be neglected.

The concentrations of most, if not all, of the constituents of CSO's vary over the course of a runoff event, as demonstrated by Colston (1). The empirical equations relating some of the constituents to the elapsed time during a runoff event were presented earlier in Table 5. Because the concentration may vary markedly, the time dependent nature of storm events has to be incorporated into the transport model.

Several workers have presented data for the variations of constituent concentrations in CSO's during runoff period. Some of the data for suspended solids are presented in Figure 6 along with three hypothetical curves obtained from Table 5. It is quite evident that the suspended solids concentrations, and therefore loads, vary with time. The equation obtained by Colston does not appear to fit these data as there is evidently a more rapid tailing off of the concentration of suspended solids in all cases than predicted by the hypothetical equation. Developing a more raliable equation would require collecting a significant amount of additional field data.

One equation that qualitatively fits the limited data available is:

$$TSS = 35Z^{0.85}\ t^{-1.25} \qquad (5)$$

Where:

TSS = total suspended solids, mg/ℓ
Q = flow rate, cfs
t = time from storms start, hrs

Also,

$$TSS = 1.6\ Q^{1.85}\ t^{-1.25} \qquad (6)$$

Where:

TSS = total suspended solids, lb/hr

As a first estimate, lacking additional data, either these equations or the equations obtained from Table 5 may be used to estimate the time dependence of suspended solids in CSO's. However, when the regression analysis work on the data by Huber et al., (15) is completed, better data should be available for the time dependence of a variety of water quality parameters in CSO's.

Summary of Characteristics

Combined sewer overflows are made up of urban surface runoff and sanitary sewage. The contribution of sanitary sewage to the total flow may be negligible in many cases, although its effect on time dependent changes in the CSO's may be important.

Urban surface runoff makes up the majority of a CSO in most cases. The characteristics of urban surface solids may, as a first approximation, be considered similar to those of street surface solids.

THE RECEIVING WATER ENVIRONMENT

Introduction

In the previous subsection the characteristics of CSO sediments relative to transport were considered. In this subsection, the impact of these sediments on the receiving water and vice-versa will be considered. The

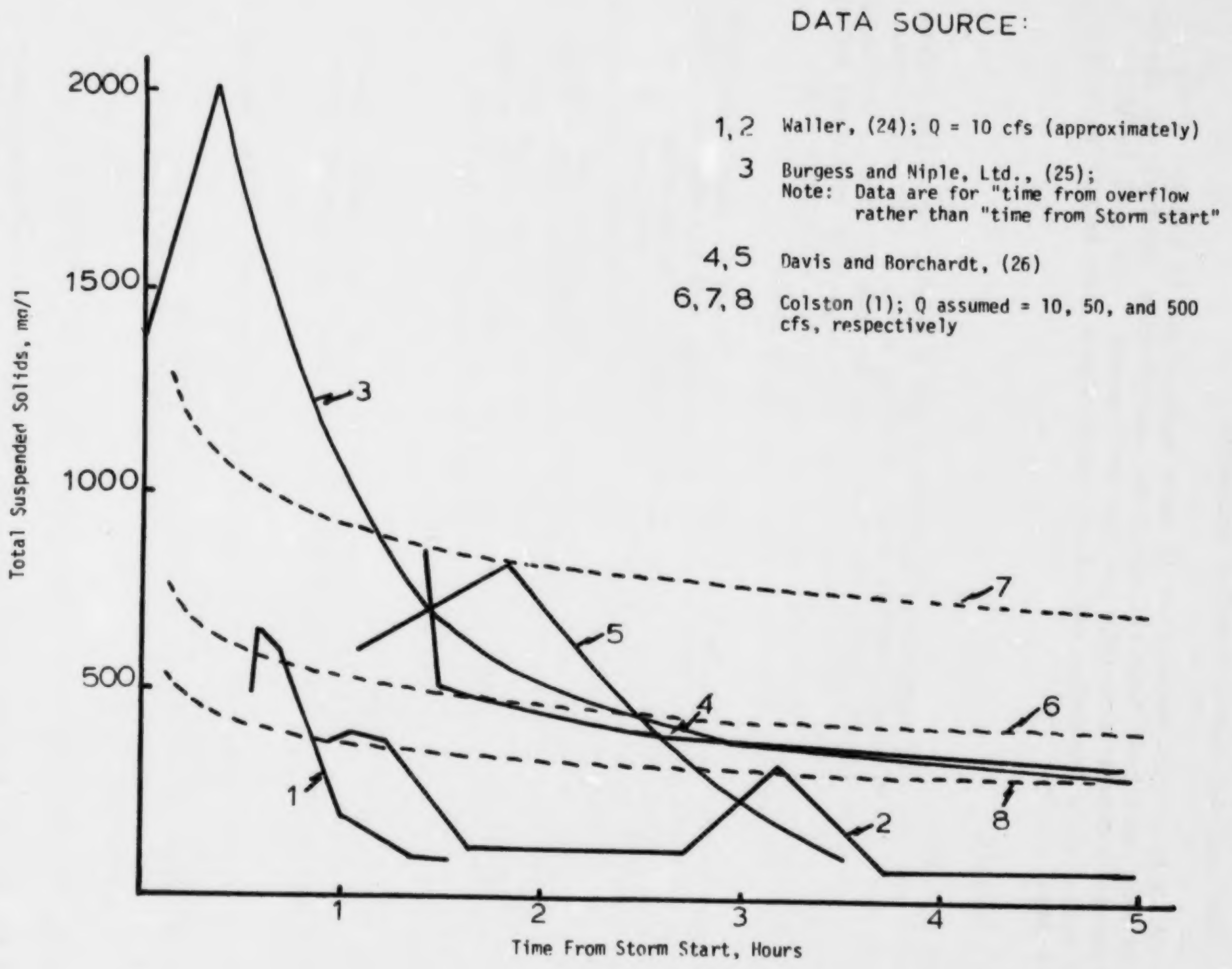

Figure 6. Time Dependence of Suspended Solids Concentrations in CSO's

chemical aspects of the interaction between the receiving water and the sediment material will be presented first. Then the potential impact of the sediment material on the biologic community will be presented. The last part in this section will present an approach for assessment of the environmental impact of the combined sewer overflow sediments.

The content of this subsection is more speculative in nature. Very little, if any, data have been collected to specifically identify the interaction between sediment materials and the environment. The goal is to identify areas where knowledge exists and areas where more knowledge would be beneficial.

Potential Impacts

Suspended Solids--

One of the readily identified impacts of CSO's in the receiving waters is the increase in suspended solids load. Randall et al., (16) quantified sediment loads from runoff events and found that for the particular drainage basin studies, only about one percent of the total amount of suspended solids load transported by the receiving stream was associated with base flows. The remaining 99 percent was associated with runoff events.

Solids associated with CSO's can have direct impact on receiving water qualtiy by decreasing the depth of light penetration and thereby decreasing photosynthesis by modifying the thermal and hydraulic characteristics of the stream and by physically interfering with biological processes (for instance, by burying the bottom dwelling or benthic organisms). CSO solids generally include materials such as heavy metals, pesticides, and organics which can affect the biology and chemistry of the receiving water. These types of impacts, if they occur, may be much more significant than the direct physical impact of the solids themselves. Impact analysis is somewhat complex, however, since the mere presence of a material does not necessarily imply that is has an impact.

Physical and Chemical Impacts--

Adverse impacts of CSO's could include physical and chemical impacts. In evaluating potential impacts, three types of relationships are quite important. These are:

(a) the specific form of the material or characteristic of the parameter responsible for the impact,
(b) the magnitude-duration of impact relationships, and
(c) the environmental fate-time relationship for the material on parameter of interest.

An example of these types of relationships is the following:

> A particular sediment size fraction (a) may have an adverse impact on algal production and fish life when above a certain concentration for a certain amount of time (b), and may be removed from suspension by physical transport processes at a certain rate (c). Relationships

of these types are important in assessing the potential impacts of any parameter of concern. Unfortunately, few such relationships have been investigated.

Physical impacts of CSO's could include hydraulic effects and impacts due to sudden increase in suspended solids loads. Increased flows could sweep organisms, both free-swimming or floating and attached, downstream. Increased suspended solids loads could reduce the depth of light penetration, potentially affecting the population dynamics, and could physically bury benthic organisms. Both transport from urban surfaces and resuspension of bottom sediments could account for the increased suspended solids loads.

The importance of CSO's in producing these types of impacts would depend largely on the hydrology of the drainage basin. The proportion of the total streams flow contributed by CSO's would be an important variable. In assessing the physical impacts of CSO's on receiving waters, the actual effects on the ecosystem should be determined in terms of the three types of relationships discussed earlier.

Adverse chemical impacts could include detrimental effects to the ecosystem of the receiving waters, a fish kill, for example, and effects impairing a downstream beneficial use, such as an increased salt content making the water unacceptable for irrigation. It is well known that the types of relationships involved in creating the adverse impact, listed earlier, are important here. For instance, only certain chemical forms of particular materials affect organisms. The organisms must be exposed to certain concentrations for certain time periods, and the chemical forms can change over time to forms which may have increased or decreased effect. These types of phenomena should be considered in predicting or assessing impacts.

Interaction of CSO Material With Receiving Water

Chemical interaction of CSO material and the receiving water depends on the types of material present. Numerous kinds of materials have been identified in CSO's and data characterizing CSO's in terms of composition are presented in the previous subsection of this report. In terms of overall transport, CSO's are characterized by the mass of material in each of seven categories: rock, metal, paper, vegetation, wood, glass, and rubber.

Chemical Composition of CSO Solids--

Data have not been collected to completely describe the chemical composition of CSO solids. The composition would vary over time and from location to location, so data of this type would probably not be useful if they were available. A reasonable approach is probably to describe CSO's in terms of the seven classes of material listed above and then to characterize a particular CSO in terms of any individual materials of interest by onsite sampling and analysis.

The material characteristics that may be important include:

- --particle size,
- --particle shape,
- --particle charge,
- --material density,
- --material coordination number,
- --oxidation state, and
- --material concentration.

Receiving Water Characteristics--

The general receiving water characteristics that may be important include:

- --pH,
- --temperature,
- --hardness,
- --alkalinity,
- --nutrient level,
- --dissolved oxygen level,
- --oxidation-reduction potential,
- --turbidity,
- --density, and
- --viscosity.

Potential Interactions--

Reactions that will be important in governing the transport of CSO materials in the receiving waters will include those that change the physical characteristics of individual particles. These reaction mechanisms will include:

- --sorption,
- --solubility,
- --oxidation-reduction,
- --complexation, and
- --biochemical reactions.

In modeling the transport of discrete, inert particles, only the physical characteristics of the particles are important. The transport variable of most importance is the particle fall velocity. In the case of CSO's additional transport variables must be considered. These might be considred as "process" variables and include particle cohesiveness and particle degradation of aggradation potential. These process variables involve the reaction mechanisms previously listed but are considered separated partly because they will be more easily observed.

Models of sediment transport incorporate certain physical characteristics of the river or stream. These characteristics include:

- --flow velocity,
- --flow depth, and
- --channel dimensions.

Interaction Process Description--

Having identified most of the important variables involved in transport of CSO solids, the next step is to organize these variables into a systematic process description. Simplifying assumptions, in addition to those made in selecting the important variables, might then be made in a logical way, with some understanding of their effects on the final results.

The transport process is depicted schematically in Figure 7. The solids and the receiving water interact according to the reaction mechanisms identified previously to yield a variety of types of particle physical characteristics. These particle characteristics are further changed by the physical characteristics of the receiving water body to result in the transport variables. The transport variables govern the resulting CSO solids transport. It is not known at this time if CSO solids transport differs to any great degree from conventional sediment transport.

The interaction between the material and water characteristics and the reaction mechanisms may perhaps be seen more easily in the form of a matrix. Such a matrix is shown in Figure 8, which estimates of the relative importance of the various interactions are given. These estimates are quite important because they could serve as a basis for simplifying an obviously complex system, and their validity should be investigated further. There will be other interactions to consider for each material (such as whether a particular reaction involving one material or water characteristic will affect another characteristic) as well as interactions among the various materials.

The reaction matrix is sufficiently complex and data so totally lacking that at this time the best approach seems to be to ignore the complexity altogether. A good data set will have to be collected which can be analyzed, to determine if it is adequate to assume that all CSO material is noncohesive and inert. If such an assumption is not adequate, then the interaction matrix approach may be used to investigate better assumptions.

Impact Analysis--

In general, the criteria for identifying streams which are potentially hazardous with respect to the deposition of CSO material are not simple and clearcut. More often than not, a hazardous situation will involve the combined action of several factors. Taken individually, none of the factors might cause objectionable conditions; taken collectively, however, the addition or subtraction of a single factor might radically alter the entire picture.

The development of a hazardous situation obviously implies the requirements that there be (1) uptake and concentration of significant quantities of pollutants by CSO and stream sediments, (2) stream geometry and sediment conditions conducive to extensive local deposits of contaminated sediments, and (3) a rate of buildup of pollutants in deposits which exceeds the rate of natural reentrainment and dispersion.

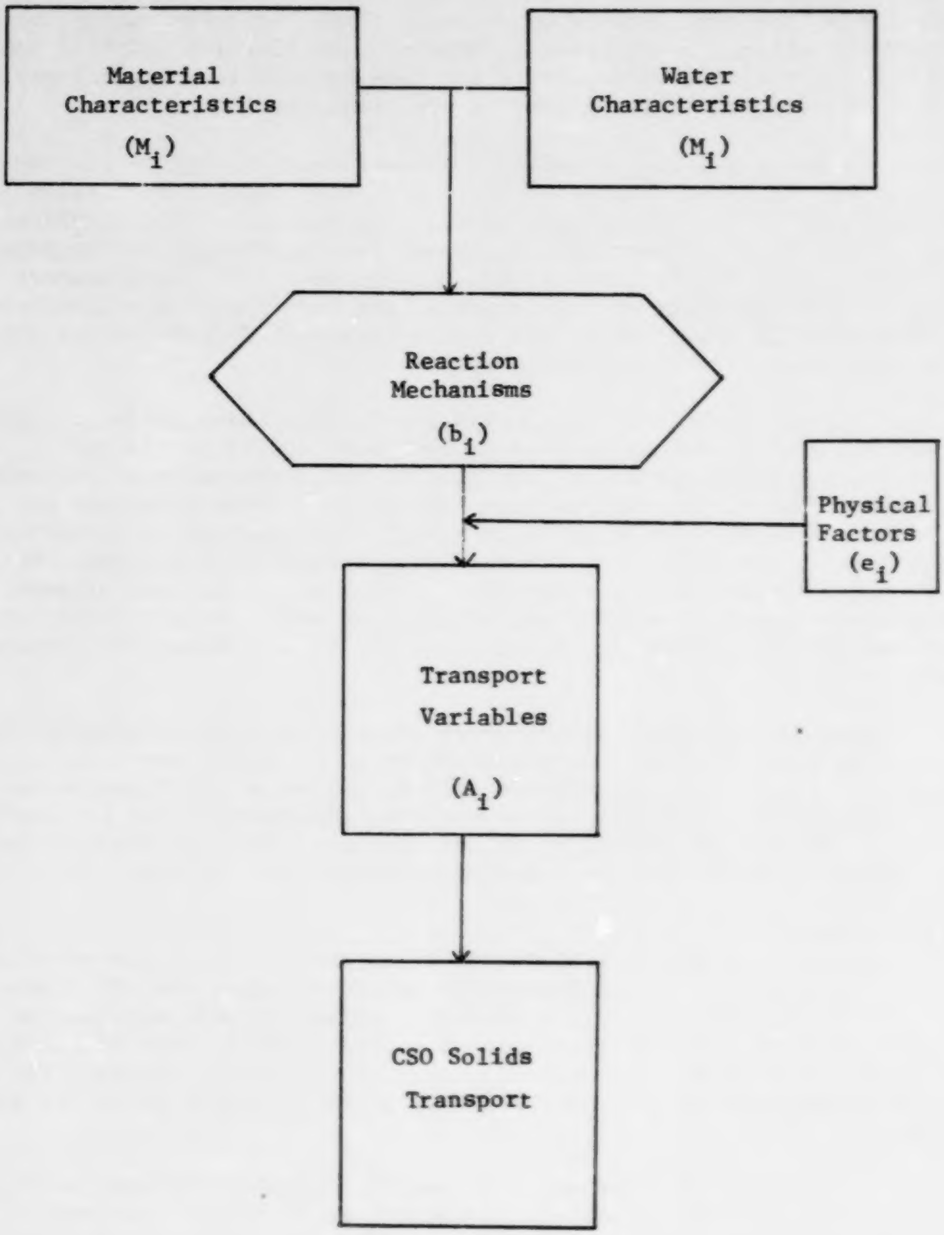
Material Characteristics
(M_i)
Water Characteristics
(M_i)
Reaction Mechanisms
(b_i)
Physical Factors
(e_i)
Transport Variables
(A_i)
CSO Solids Transport

Figure 7. Schematic Diagram of CSO Solids Transport Process

W_i	Sorption	Solubility	Redox	Complexation	Biochemical
pH	1,B	2,B	1,A	1,C	1,A
Temperature	1,C	1,C	3,C	1,C	1,C
Hardness	1,B	2,B	3,C	2,C	3,C
Alkalinity	2,C	2,B	3,C	2,C	1,A
Nutrients	3,C	2,B	3,C	2,C	1,A
DO	3,C	2,C	1,C	3,C	1,A
Turbidity	1,C	3,B	3,C	3,B	1,A
M_i					
Concentration	1,A	1,A	1,A	1,C	1,A
Size	1,C	1,A	3,C	3,C	1,A
Shape	1,C	1,A	3,C	3,C	1,A
Charge	1,A	3,A	3,A	3,A	1,B
Density	3,C	3,A	3,C	3,C	3,A
Coordination Number	3,C	1,A	3,C	1,C	3,B
Oxidation State	2,C	1,C	1,A	3,C	1,A

Key:

Reaction is affected by W_i or M_i

1 - almost always
2 - dependent on material
3 - rarely

Reaction affects W_i or M_i

A - almost always
B - dependent on material
C - rarely

Figure 8. Reaction Mechanisms and Material Interactions

With respect to the sediment itself, the total available surface area of the suspended-sediment particles is the most obvious index of hazard potential. Concentration and sizedistribution are fairly reliable indicators of surface area.

Fortunately, the greater sorption capacity of the fine sediments is to some extent offset by the tendency of colloidal materials to remain in suspension except when flocculation occurs. Heavy concentrations of contaminated fine sediments might occur in density currents at the bottom of reservoirs and pools.

The concentration and load of suspended sediment in streams can be considered one of the important criteria for indentifying potentially hazardous streams because of the effect on amount of available surface area for sorption. Further, it is important as a factor in the nature and extent of deposition and erosion within the stream system.

The nature of the concentration and (or) load variation with respect to time may be important because it is expected to indicate the capacity or lack of capacity of the stream to transport a given input of waste. For example, a stream with a relatively uniform water discharge and high concentration of fine sediment would probably maintain the waste in suspension on, or with, the fine sediment. On the other hand, a stream with a large range of water discharge and sediment load receiving the same concentration of waste would be expected to carry the waste in "slugs" because the waste not having an abundance of fine suspended sediment for sorption during low flow periods would probably be sorbed on the particles in the stream bed. Then, during the relatively short periods of storm runoff with high concentrations of sediment, the waste held on the bed may be exchanged to "free" suspended particles and (or) moved downstream considerable distances as bedload.

Conditions conducive to the formation of sediment deposits containing large amounts of CSO discharge wastes are more likely to be found on the inside of a bend on a stream near the source of waste disposal rather than on the banks of a straight stream channel, on a stream exhibiting a considerable range of sediment concentration and water discharge rather than a stream of nearly uniform water discharge and sediment concentration, and on a stream with man-made channel controls rather than on an uncontrolled stream. (The Cuyahoga River, evaluated in the next section of the report, is a good example of a stream with man-made controls.)

Sediment of the coarser fractions, usually deposited on the point bar on the inside of a stream bend, is derived mostly from that being cut from the outside bank of the opposite bend immediatley upstream. The finer fractions, usually deposited only at the upper elevations of the bar, or during the recession of the storm runoff event, may be derived from many sources including bank cutting in the immediate channel, or gully and sheet erosion in the upper part of the drainage basin. The point bar at the first bend immediately downstream from a source of waste may then be built of a large mass of contaminated sand. In this discussion, it is assumed that the waste is sufficiently mixed with stream flow so that contact with the sediment in transport is relatively uniform.

Streams of widely varying discharge are conducive to bank and flood plain deposits. The most rapid deposition on the inside bank of the meandering channel occurs during the high rates of flow; especially so, for the fines at the top of this deposition bank. Flood plain deposits obviously cannot occur without the generally unusual high rates of flow. Deposits of fines along stream banks other than point bars usually occur during the recession of a storm event for which relatively large concentrations of fines are carried These may be of only minor significance because they are transported and deposited when stream flow and concentrations are considerably greater than average and, therefore, the concentration of waste in the deposit is likely to be low. This again assumes a uniform rate of waste disposal.

Deposits of contaminated sediment may accumulate within the controlled channel when flow and sediment concentration are low for long periods of time; and thus, with a constant rate of waste disposal, the concentration of pollutants in the water and on the sediment would be high. Similar to channel control, the most critical deposits in the pool-and-riffle type of stream fines are deposited in the slack water resulting in an intensive concentration of CSO material in the pool. With this type of stream the deposit is usually removed during the rising stage of the next period of storm runoff.

The hazard potential of CSO material in streams may be considered in view of differences in stream flow, in channel geometry, and in the concentration and character of sediment as they may affect deposition of sediment and consequent waste. However, streams are very complex with respect to the magnitude and variation of these features; and, therefore, classification according to hazard potential is difficult and indeed almost remote in view of limitations concerning basic knowledge of the relation of these features.

For example, a stream with relatively large water and sediment discharges may be conducive to extensive deposition and erosion within the channel; but, because of the high rates of water and sediment movement, the concentration of waste may be very low. Further, a meandering channel results in a nearly continuous building of a deposit as a point bar, but most of the building occurs during high rates of water discharge when the concentration of waste in the water is low.

The sand-bed stream of good alignment and carrying a relatively uniform water discharge and concentration of fine sediment would be the least hazardous kind of stream to transport a given uniform amount of CSO material without accumulating extensive and (or) concentrated deposits. Such a stream would have relatively minor and uniformly concentrated accumulation of waste in relation to both time and space in the bed and along the banks.

One of the most hazardous conditions may occur either on the pool-and-riffle type of stream or a large river controlled with low dams for navigation purposes. For these situations, the pool or pools immediately downstream from the disposal outlet may accumulate extensive deposits in the bottom of the pools. This results from the relatively low water discharge and the very low concentration of sediment, and consequently, a very high concentration of material accumulating for long periods of low water flows. When a relatively large increase in flow occurs after weeks of months of accumulation, most of the contaminated deposit will move downstream and thus become available for bed, bank, or flood-plain deposition (27).

Only after the movement and resting places of the CSO sediments have been identified will it be possible to determine biologic input. For instance, deposition rates in shallow areas can be compared to allowable rates for fish spawning. Deposition depths and residence thus can be used to determine if certain plant species would proliferate or die out. A knowledge of the oxygen demanding material present in the sediments, along with transport information, could be used to assess DO impact. None of these things can be done with certainty at this time.

In the following section of the report, the current state of sediment transport modeling is discussed. Such models, along with suitable verification data sets, are vital to address the data question. Once transport paths and data are identified, then impacts can be intelligently addressed.

Biologic Community of Receiving Waters

Introduction--

The purpose of this section is to identify both the plant and animal communities near combined sewer overflows and to briefly describe some of their relevant characteristics (28,29). The discussion will be centered around rivers and streams since this is where most sewer overflows are received. Characteristics will be limited to those that may in some way affect or be affected by sediment transport.

General Description--

The aquatic environment is comprised of water, its chemical impurities, and its various life forms including bacteria, phytoplankton, zooplankton, fish and benthic animals. There are a number of approaches to the systematic description of plants and animals living in the aquatic environment. In this section, plants will be described by categorizing them into five basic divisions: phytoplankton, flowering plants, ferns, moss and liverworts, and fungi. An alternate method of description that will only be given a cursory treatment, is to categorize plants by way of zonation, i.e., what depth of water they have adapted to. Animals will be described by their level of development, i.e., trophic levels.

The flora and fauna of rivers change in character as one moves from the headstream to the mature lowland river. Animals in headstreams, for example, must either have hooked appendages or suckers or be sufficiently strong swimmers to maintain their position against the high velocity of the water. Animals in mature rivers do not need appendages or strong swimming muscles but must be tolerant of turbid and silting conditions, and must be resistant to conditions of low oxygen tension and of high and variable temperature.

Transition in river characteristics are not abrupt; however, there are four zones that may be identified. The first is the "very rapid" zone found generally in areas of steep gradient; the second is the "moderately swift" zone usually with a bottom of stones and boulders; the third is the "moderate current" zone, usually with a gravelly bed; and finally, the "medium to slow" zone generally found in lowlands.

From headstream to mature river, a decreasing gradient is observed; a gradual passing occurs through the four zones. During this transition, one notes: a decrease in current velocity; a change in the bottom deposits as a result of the decrease in erosion and transport capabilities of the water from large rocks in headstreams through lesser sizes of gravel to sands, and finally silts in the mature river; increasing average temperature; and increasing range in daily and yearly temperature; and a decreasing dissolved oxygen content of the water. The changes are most pronounced in the range just below the source.

In general, the human development of urban areas is restricted to relatively flat locations. As a result, the "moderate current" and "medium to slow" zones will be of greatest interest.

The Plant Community--

In a simplistic model of life, plants convert inorganic nutrients into organic matter by using energy from the sun. Plants are consumed by herbivores (plant eaters) which, in turn, provide food for carnivores (meat eaters) which die and are decomposed to inorganic matter by bacteria and fungi. This constant recycling of matter is known as the food web.

Plants occupy the primary positions of the food web. The main divisions of the plant kingdom are the algae (or phytoplankton), flowering plants, ferns, mosses and liverworts, and fungi, all of which are represented in the aquatic environment.

Phytoplankton--

In general, these are the most important organisms in the aquatic world. Phytoplankton are actually comprised of photosynthetic microorganisms of which diatoms (single celled algae with hard outer coverings of silica) are the most abundant. Phytoplankton are important because they are a primary producer of organic matter in the pyramidic food chain (Figure 9) and are a major source of dissolved oxygen in natural waters. Physical factors influencing river algae are the right size of the stream, current rate, water level, depth, temperature, light, and turbidity.

Turbidity has a great effect on algae. Studies in Georgia and Alabama compared algal populations in a very turbid stream and in a relatively clear, associated stream. The algal population in the turbid stream was between 126 and 422 cells/mℓ, and the genera did not exceed two. In the clear stream sampled the same day, the algal population numbered 6,075 cells/mℓ and genera, excluding diatoms, numbered 10. Increased complexity in a food web can create an increased stability of a stream community by offering alternative food sources to consumers; thus excessive turbidity can destroy this complexity by decreasing the diversity of species. Turbidity is associated with the extremely fine clay range of sediment sizes. This is an area where modeling capabilities are lacking at this time.

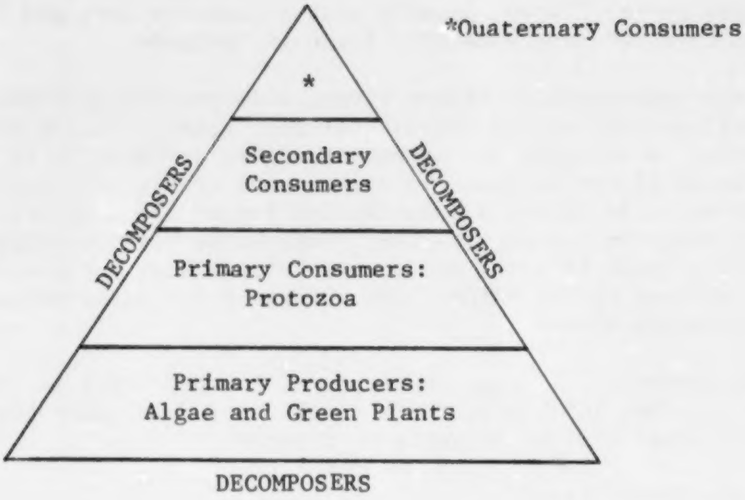

Figure 9. The Pyramidic Food Chain (28)

Flowering plants--

Flowering plants are another major primary producer. It is convenient to categorize flowering plants into three types: (1) emergent plants, (2) floating plants, and (3) submersed plants. Plants that grow in the soil with only their lower portions submersed are called emergent vegetation. Less of the plant body is supported by buoyancy and more synthetic activity is invested in the buildup of supporting tissues containing cellulose. These plants decay at a lower rate since most aquatic herbivores cannot metabolize cellulose directly. Examples of emergent vegetation include cattails, arrow arum, wild calla, and arrowhead.

Floating plants are generally rooted with just their leaves on the water's surface, but a few are actually free-floating. Examples include duckweeds, wolfiella, and hyacinths.

Submersed plants are those that are completely covered with water. They form large, dense masses, especially in late summer, that are extemely important as a source of shelter, food, and materials for nest building for life beneath the surface. Examples include the water cress, water worts, alligator weeds, mare's tail, and beggar-ticks.

The abundance of aquatic plants is very important to the productivity of natural water. The existence of invertebrates is closely related to aquatic plants; they tend to select those plants with compact, finely branched leaves. So important are aquatic plants that their abundance can be used as an "index of productivity" for fish.

The interaction between the plant community and sediment transport is intuitively obvious but poorly investigated. Plant species are one important component of resistance to flow. Conversely, sediment deposits can smother low growing vegetation. Turbidity can shut off light supplies for photosynthetic activity. No quantitative studies of these interactions exist.

Ferns--

The third major plant division is the ferns. Ferns are a widespread class of nonflowering plants having roots, stems, and fronds (leaves) that reproduce by spores instead of seeds. Aquatic examples include the quillwort, pillwort, and horsetail. The rest of the 8,000 species of ferns are shade-loving terrestrial plants.

Mosses and liverworts--

These are occasionally called the amphibians of the plant world. They are more advanced than the algae but do not have conducting and stiffening tissue or true roots as do the higher plants. They often form extensive "green carpets" where the substream is rocky or stony and provide a foothold for animals which would otherwise be swept away by the current. The water must be relatively clear for them to carry on photosynthesis at the bottom of the stream. They are thus quite sensitive to turbidity or buried by large scale deposition.

Fungi--

The fifth division is represented by many small and inconspicuous species including molds, mildews, mushrooms, rusts, and smuts. These are all parasites on living organisms or feed upon dead organic material. Thus, they play an important part in the decomposition of organic matter and as disease-producers in higher plant forms.

The Animal Community--

Recent literature has begun to abandon the rather simplistic "food chain" concept and is adopting what is called the "food web." This latter term suggests a more complex interaction and is shown in a simplified matter in Figure 10 (29). The animal kingdom and its members appear near the bottom of the food web. The members will be discussed individually.

Zooplankton--

At the lowest level of development in the animal community are the zooplankton or the animal portion of the plankton. This term includes protozoa rotifers, and other microscopic creatures. As with their plant counterparts, zooplankton are of greatest importance in large, slow-moving rivers because of the tendency of rapid current to wash them downstream.

Rotifers--

Rotifers make up the greatest share of zooplankton. They feed mostly on minute organic particles; however, a few are predatory on other organisms and a few feed on the fluid contents of filamentous algal cells. Rotifers are largely associated with the substrata.

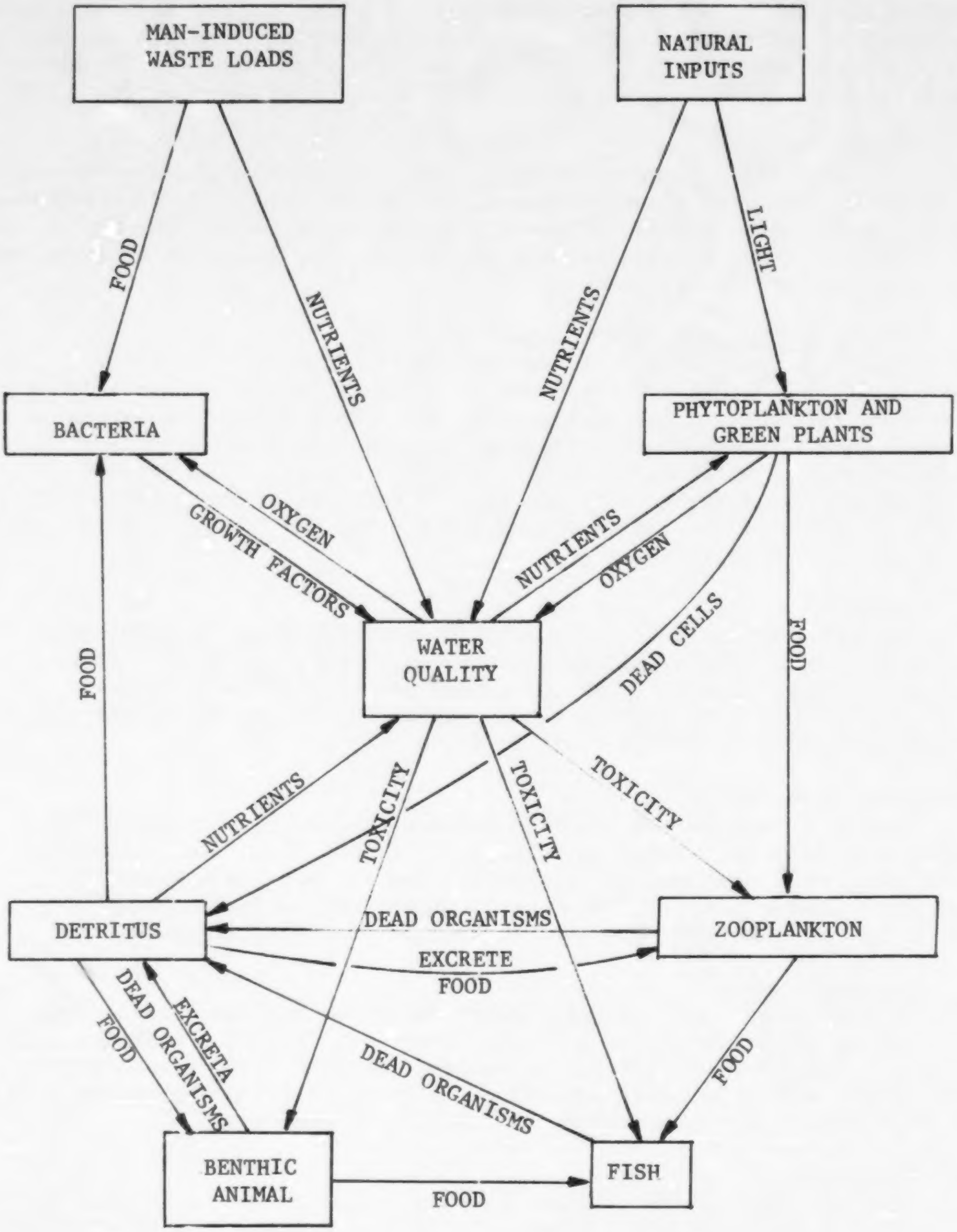
MAN-INDUCED WASTE LOADS
NATURAL INPUTS
FOOD
NUTRIENTS
NUTRIENTS
LIGHT
BACTERIA
PHYTOPLANKTON AND GREEN PLANTS
OXYGEN
GROWTH FACTORS
NUTRIENTS
OXYGEN
DEAD CELLS
FOOD
FOOD
WATER QUALITY
NUTRIENTS
TOXICITY
TOXICITY
TOXICITY
DETRITUS
DEAD ORGANISMS
ZOOPLANKTON
EXCRETE
FOOD
FOOD
DEAD ORGANISMS
EXCRETA
DEAD ORGANISMS
FOOD
BENTHIC ANIMAL
FOOD
FISH

Figure 10. Definition of Aquatic Ecosystem (29)

Protozoa--

The Protozoa are perhaps the least understood group of aquatic animals. A majority of Protozoa are attached to the substrata and are particularly abundant in habitats of active decomposition. They are extremely important as a major metabolizing organism of dissolved and particulate organic matter in sewage treatment facilities and organically polluted streams. The very large and varied feeding capabilities (algae, bacteria, particulate deritus, and other protozoa) together with their large population densities on aerobic, organic-rich sediments are all indicative of their significant metabolic role in freshwater systems.

Planktonic crustaceans--

The groups Cladocerans and Copepods nearly dominate the truly planktonic (freeliving) crustaceans. The seed shrimp is an example of a crustacean that is primarily a benthic animal. They resemble tiny clams and are usually around 1 to 3 mm long. For the most part, seed shrimp are scavengers, filtering the water to remove bacteria, molds, algae, and general detritus. They generally creep about in the algae or over vegetation, or burrow in the mud and ooze of the bottom. Many can survive long periods of stagnation with little oxygen. Crustaceans are likely to be associated with backwater areas and slow moving portions of rivers where fine material deposits form.

Mollusca

The phylum Mollusca, which includes the chitons, oysters, clams, mussels, snails, whelks, slugs, and other invertebrates, is one of the least advanced phylums but is very important in the aquatic environment. They make up a large percentage of the benthic animals and together with insect larvae and nymphs, crustaceans, worms, leeches, and sponges make up the bulk of the intermediate trophic levels. The largest number of benthic animals are found above the compensation level (where photosynthetic activity is equal to respiration).

Snails and limpets--

Snails and limpets move by sliding across the substratum and maintain their position against the force of current by viscosity. Snails and limpets are able to remain submerged indefinitely. They feed on the microscopic algae that coat submerged surfaces, filamentous algae, and other green vegetation as well as on dead plant and animal matter (detritus). They require a high oxygen content (limpets even require oxygen-saturated water) so are seldom found in polluted water. They are also rare in swift streams where the bottom is sandy and gravelly.

Bivalves--

The bivalves include clams and mussels and are most common in the muddy bottoms of large rivers. They range in size from 2 mm to 250 mm. Bivalves move in much the same way as snails, and feed on microscopic plankton and microscopic organic debris washed into the water. Fish include them in their diet.

Worms--

Small, often microscopic worms crawling over vegetation or debris, make up another large portion of the benthic animals and are of tremendous importance in the economic life of any body of water. They are scavengers and feed on bits of organic material or upon small plants, transforming these substances into animal tissue that can nourish larger invertebrates and even small vertebrates. Occasionally, worms will feed directly upon other small animals. They are preyed upon by other worms, crustaceans, insects, and fish. Most worms are negatively phototactic and thus occur as much as 4 cm under sediments and debris and in shaded parts near rocky substrata and macrophytes. A number of worms, in particular flatworms and nematodes, greatly increase as a stream or lake becomes polluted with organic matter.

In the Milwaukee River at Milwaukee, Wisconsin, sludgeworms attained populations of 84,000 per square foot of river bottom due to an inexhaustible organic food supply. Immature stages of mayflies, caddises, and hellgrammites, were eliminated. In the Brule River bordering Michigan and Wisconsin, where man-associated organic wastes are not a problem, clean water larval caddisfly populations number around 1,100 per square foot.

Sponges--

The sponge is a plantlike animal usually found in the ocean. A few freshwater species do exist--however, when conditions are favorable. Sponges feed by maintaining a current of water through their bodies by means of flagella. Microscopic organisms are filtered out and used.

Insects

Insects are animals of the phylum arthropoda, having six legs and usually one or two pairs of wings. Insects are a mjor importance in the balance of nature. They aid bacteria and fungi in the decomposition of organic matter and in soil formation. For example, the decay of carrion brought about mainly by bacteria, is accelerated by the maggots (larva) of flesh flies and blowflies.

Insects that have adapted to the aquatic world have had to make substantial modifications in their respriration in order to survive. Many rise to the water surfaace and take air into their tracheal systems, some prolong submergence by trapping air among their surface hairs, and other insects have adapted to the point of being able to obtain all of their oxygen from the water (e.g., midge larvae, amyfly larvae, and dragonfly larvae).

Spiders and mites--

Arachnids (i.e., spiders and mites) differ from arthropods in having no antennae, four pair of long six-segmented legs, and only two pair of mouthparts. Spiders are not truly aquatic although a few are consistently associated with freswhaters. They are normally insectivores.

Mites, on the other hand, creep about on the bottom and on vegetation. They are carnivorous or parasitic, feeding on insects and worms, piercing their victim to draw out the juices. Insects and fish include mites in their diet.

Fish--

The most advanced phylum in the aquatic world is Chardata, which includes all those animals with a backbone: fishes, various amphibians, birds, and mammals.

Freshwater fish may be conveniently grouped as to their feeding habits (30):

(1) Parasites. Feed on blood and bloody fuilds or other fish, e.g., Lampreys.

(2) Plankton feeders. Having close-set gill-rakers. They often show a migratory pattern, following the fluctuating plankton population, e.g., Golden Shiner, Minnows, Paddlefish, Young Bass and Trout.

(3) Bottom feeders. Obtain food by sucking. Many locate their food by sensitive barbels hanging below the head and are often seen swimming a short distance above the bottom with barbels dragging. The stoneroller, however, picks up food with its protruding lower jaw, e.g., Catfishes, Paddleifhs, Sculpins, Stoneroller, Sturgeon, Suckers, Sunfishes, Whitefish.

(4) Vegetation feeders. Spend much of their time browsing or nibbling on vegetation. They also feed on invertebrates, e.g., Cap, Creek Chub, Eels, Golden Shiner, Goldfish, Killifishes, Minnows, Sculpins.

(5) Invertebrate feeders. Prey on insects and crustaceans mainly. They also feed on Mulluscas. Includes the majority of freshwater fish.

(6) Invertebrate feeders. Also prey on fish and other vertebrates, e.g., Bass, Bowfins, Turbot, Darters, Eels, Sculpins, Sunfishes, Trout, Walleye, Yellow Perch.

(7) Vertebrate feeders. Use their long sharp teeth for grasping frogs, snakes, and even turtles as well as many fish, e.g., Gars, Pickerel, Pike, Muskellunge.

(8) Notorious omnivores. e.g., Catfish.

It should also be noted that fish such as the trout are extemeley sensitive to reduced dissolved oxygen, whereas buffalo fish, sticklebacks, the carp, and the gar are quite tolerant of this condition.

Bacteria--

Bacteria, as well as fungi, are the recyclers, breaking down animal and plant tissue into forms available for the lower trophic levels. Without them, life would be impossible.

In unpolluted waters, away from the more nutrient shores, the number of bacteria is small on the order of a dozen per milliliter. The kinds of bacteria present is greatly influenced by the amount of dissolved oxygen present. Another important factor is the type of food present at the time. For example, if a tree falls into the water, the whole flora is changed; cellulose-digesters and fermentative types thrives as do saprohpytes. The concentration may reach 100,000 per milliliter unitl an equilibrium is again reached.

In streams polluted with organic material, *Escherichia coli* and other *Enterbacteriaceae*, as well as fecal streptococci and various species of intestinal Clostridium are present in large numbers. Many soil saprophytes, yeasts, and molds find organic wastes excellent food. The number of microorganisms in a heavily polluted stream may reach into the millions per milliliter. In the process of decomposing organic matter, aerobic bacteria consume oxygen and may cause a DO deficit if too much feed is available to them.

Summary of Impacts on Biologic Community--

The food web in the aquatic environment is an extremely complex mechanism. Its balance may be upset in a number of ways, many of which are natural. Figure 11 shows some of the ways in which man made pollution may affect life in rivers. Sediment transport may play a role in virtually all the illustrated effects.

At this time it seems impractical to define precise impacts of CSO sediments on aquatic life. This is because the fate of the sediments is only partially understood. However, the next section will consider assessment approaches.

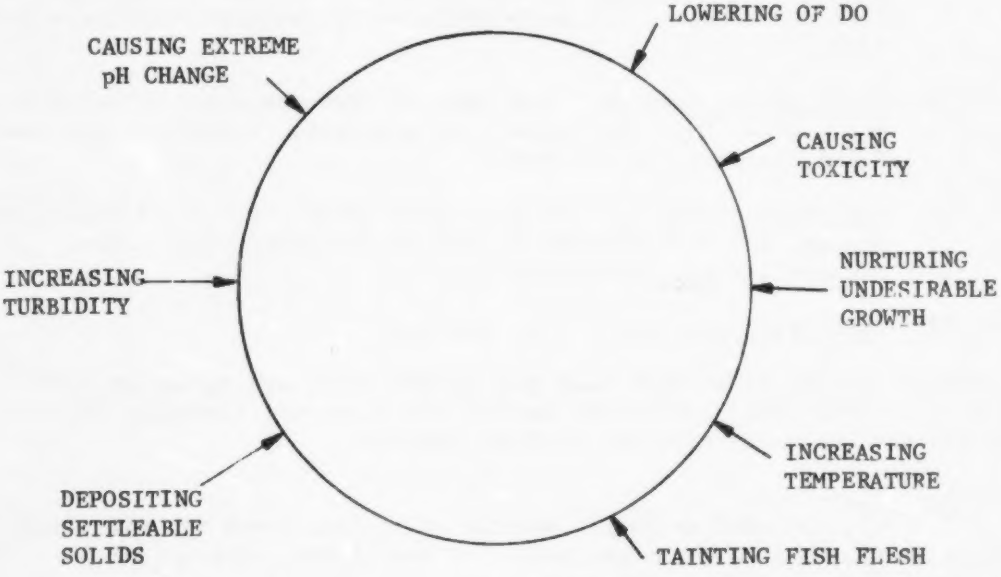
LOWERING OF DO
CAUSING EXTREME pH CHANGE
CAUSING TOXICITY
INCREASING TURBIDITY
NURTURING UNDESIRABLE GROWTH
INCREASING TEMPERATURE
DEPOSITING SETTLEABLE SOLIDS
TAINTING FISH FLESH

Figure 11. Environmental Factors Which Produce Undesirable Effects in Aquatic Life

Approach for Assessment of Environmental Impacts

The U.S. is entering an era when the costs of control of contaminants from various sources will be weighed against potential environmental impacts of failing to control these contaminants, or only partially controlling them. Within this framework, it is important to ask: What are the real environmental impacts of combined sewer overflow? How significant a problem is this today? Can treatment, where needed, be directed toward those particular contaminants of greatest concern? The concept of separating storm and sanitary sewers in major municipalities has largely been abandoned by those responsible for developing these programs because of the very high costs. Therefore, the cost-effective ecologically sound approach which should be used for control of the overflow is one of evaluating where there are real environmental problems of major significance caused by combined sewer overflow from a particular municipality, and then taking steps to eliminate these problems. Ultimately, if sufficient funds are made available, some of the instances of combined sewer overflow of lesser importance in terms of environmental degradation, can be corrected.

Basically, what is needed in the solution of combined sewer overflow problems where they exist today is the development of an approach that will allow a case-by-case evaluation of the environmental significance and cost associated with controlling a particular combined sewer overflow that is occurring at a specific site or within a limited region of a municipality. This section addresses the information available today on the significance of combined sewer overflow as a cause of water quality deterioration, with particular emphasis given to the significance of suspended solids in the CSO in affecting receiving water qualtiy in the region of the combined sewer overflow point of entry to the environment.

The actual environmental impact of any particular combined sewer overflow is difficult to discern since usually these overflows occur in or to waterways which would likely be heavily impacted by municipal and industrial wastewater discharges to the waterway from sources upstream of the combined sewer overflow point of entry. Therefore, even without the combined sewer overflow, water quality in the waters receiving the overflow would usually be degraded in many municipalities. There are few studies which specifically single out combined sewer overflow as a cause of water qualtiy deterioration. The lack of studies does not mean that there has not been significant water quality deterioration because of CSO's. It is just that it has been difficult to document this deterioration because of lack of funds for field studies and the lack of attention being given to this area by those responsible for control programs within urban centers. The situation with respect to the environmental impact of combined sewer overflow solids is even worse. To the knowledge of the authors there has not been a single study devoted specifically to this topic area, where a quantifiable environmental degradation has been traced back to a contaminant load from combined sewer overflow. While there have been no studies specifically directed to this topic from the nature of combined sewer overflow contaminants, it is possible to gain some understanding of potential environmental degradation that can occur as the result of CSO's. Most importantly, guidance can be provided to those responsible for assessing the significance of CSO's in a particular locality on how they should proceed to make this assessment and thereby judge the potential benefits that will be derived from controlling the combined sewer overflows to various degrees in a particular locality.

While there is little or no information on the direct environmental impact of solids associated with combined sewer overflows, some inference on the potential impact can be obtained through the studies that have been conducted over the past half-a-dozen years as part of the Corps of Engineers' Dredged Material Research Program. In the early 1970's, considerable concern was voiced about the significance of chemical contaminants associated with U.S. water way sediments during dredging and dredged materials disposal operations. There was a strong move made by pollution control regulatory agencies to impose restrictions on the amount of open water disposal of dredged sediments because of these contaminants. The alternate methods of disposal were often significantly more expensive than the then currently used open water disposal techniques. This led to the federal Congress appropriating $30 million for a five-year study devoted to evaluating the environmental impact of various methods of dredged material disposal. This study was completed in 1978 and the results have been published in a series of reports by the Corps of Engineers Dredged Material Research Program located at the Waterways Experiment Station, Vicksburg, Mississippi. As part of this study, the authors of this section of the report conducted a five-year, over $1 million investigation in which a combination of laboratory and field studies were conducted at a variety of sites across the U.S. in order to evaluate the potential environmental impact of open water disposal of dredged sediments. The findings of these studies were published in a two-volume report authored by Jones and Lee (32) and Lee et al., (33).

The senior author of this section of the report was also involved as an advisor to the Corps of Engineers in helping to establish the overall Dredged Material Research Program and in reviewing the study results and, therefore, is familiar not only with the studies being conducted under his supervision but also with the studies conducted by other investigators as part of the DMRP.

There is considerable analogy between the environmental impact of open water disposal of dredged sediments and that associated with combined sewer overflow. Both systems have considerable amounts of solid material containing contaminants. Typically, however, the dredged sediment would tend to be inorganic in nature while the combined sewer overflow solids should tend to be more organic in nature. Further, both of these processes tend to be intermittent in which there is a relatively large input of particulates for a short period of time and then there is a period of time in which there is little or no input.

For both open water disposal of dredged sediments and combined sewer overflow, there are three basic environmental problems that must be considered. The first of these is the chemical contaminants associated with the liquid phase (i.e., the solution). The environmental impact of these contaminants can be estimated to some extent based on the concentration in the combined sewer overflow, the duration of overflow, the mixing-dispersion-dilution that occurs within the waterbody, and the ambient concentrations of the contaminants of concern in the waterbody. It is important to note that the US EPA July 1976 (34) water quality criteria (Red Book), or state standards based on these criteria, were developed for worst case situations which involve chronic exposure of aquatic organisms to available forms of the contaminants. This fact should be kept in mind when using these criteria as a basis for judging the significance of contaminants in the solution phase. The typically intermittent occurrence of both dredged material disposal and combined sewer overflow, coupled with the physical and chemical characteristics of the materials, create situations where large portions of the contaminants are in forms that are unavailable to affect aquatic life. Except in rare instances where the receiving waters have limited ability to dilute the contaminants, there will not be a chronic exposure of organisms.

The second area of concern with respect to the environmental impact of combined sewer overflow is the physical effects of the solids on benthic and epibenthic organisms in the region of the discharge, as well as any watercolumn organisms present in the discharge area. Considerable work has been done over the past several years as associated with the discharge of mining waste to the environment, which has shown that the impacts of the suspended solids associated with dredged material or tailings disposal are rarely of significance to watercolumn organisms. The American Fisheries Society and others have taken a less conservative attitude on the criteria for suspended solids than that contained in the US EPA Red Book which limits the suspended solids increase in water to a five percent change in compensation depth, i.e., the depth of the watercolumn at which photosynthesis equals respiration. Plumb and Lee (35) have discussed this point in detail in their review of the potential effects of suspended solids on phytoplankton.

Considerable work has also been done [see Pedicord et al., (36)] on the significance of supended solids to both freshwater and marine animals. It was found that many of these organisms can tolerate very high, i.e., grams per liter concentrations of suspended solids for extended periods of time without any adverse effects. Few, if any, problems would be expected to result from the presence of suspended solids in the watercolumn associated with open water dredged material disposal other than an aesthetic problem of turbid-cloudy water for a period of time, usually a few hours to a day or so, which might be readily noticeable in an aquatic environment which has a low ambient suspended solids concentration. The likelihood of problems due to suspended solids in combined sewer overflow would be even less than that for dredged sediment because of the fact that the solids content of dredged sediments is typically on the order of 25 percent sediment at the point of release. Typical combined sewer overflow would be expected to have considerably lower concentrations of solids and, therefore, except for the potential for short term aesthetic problems, would not likely be a significant factor in impairing the beneficial uses of the waterbody, as is the case with dredged sediments, does not represent a long term, continuous increase in the cloudiness of the water. Therefore, even if potentially adverse suspended and solids levels were found at the time of the discharge, because of the intermittent nature of these discharges, organisms would not likely be exposed to them for sufficient periods of time to be adversely affected. Some organisms also exhibit an avoidance behavior; they would leave an undesirable area or not enter it, thereby not being exposed to adverse conditions.

There is one important physical effect that the solids in both dredged sediments and combined sewer overflow have that can cause a significant detrimental environmental impact. This is the burying or smothering benthic and epibenthic organisms. There is no question about the fact that disposal of dredged sediment in a region where there are coral reefs, oyster beds, fisher production areas where the eggs are laid on the bottom, or in some aquatic organism nursery areas, can have a very significant deleterious effect on aquatic organisms in those regions. It is important that open water dredged sediment disposal take place in such a way so as to avoid these kinds of problems. This can usually be done through a site-specific investigation designed to detect the presence of areas ecologically sensitive to suspended solids deposition.

Since combined sewer overflow systems are no longer being constructed and ecologically sensitive discharge areas have long ago been wiped out, about all that a site-specific investigation of an area might conclude is that if it were not for the suspended solids deposition in a region, the region might have certain types of benthic and epibenthic habitat. At this time, however, aquatic biologists'-ecologists' ability to predict a type of habitat that would exist given different environmental conditions, such as with or without a combined sewer overflow, is quite limited. Normally, even without the combined sewer overflow, the habitat has been so drastically altered by other physical structures and altered flow regimes, etc., that there is little likelihood that one could predict with a high degree of reliability the potential for reestablishing certain types of aquatic habitats by elimination of a combined sewer overflow. This is an area, however, that does need research and which could be cost-effective in helping water pollution control officials to decide whether or not the control of the solids associated with combined sewer overflow situation could represent a cost-effective, ecologially sound approach toward improving aquatic habitat of a region.

The third area, which is probably of greatest concern associated with combined sewer overflow, is that of the significance of chemical contaminants associated with the solids that are discharged to the environment. Combined sewer overflow solids represent a mixture of domestic wastewaters, industrial waste, and urban stormwater drainage. All three of these sources likely have very high concentrations of contaminants associated with their solid phase. Even if the contaminants are discharged to the sewerage system in a soluble form, the relatively high concentrations of the solids present in the wastewaters and urban drainage would readily sorb many of these rendering them less available to affect aquatic life.

The Dredged Material Research Program provides considerable information that is directly pertinent to this topic area. The studies by Lee et al., (33) and Jones and Lee (32) as well as those of others, have shown that a relatively simple leaching test - the elutriate test - provides a reliable indication of the potential for contaminants associated with waterway sediments to be released to the watercolumn upon open water disposal of the sediments. A test like the elutriate test needs to be developed for combined sewer overflow in which well-defined leaching tests are run on samples of the overflow material; the amount of leached contaminants is then interpreted in terms of the concentraion of contaminants in the ambient water and the dilution-dispersion of these contaminants that takes place in the receiving waters. Since it is conceivable that contaminants associated with solids in the combined sewer overflow could be and would be released to the watercolumn under the more dilute situations that occur in the aquatic environment, a leaching test should be used. However, it is important that an approach similar to that advocated by Jones and Lee (31) be used in interpretation of the leaching test results. As noted by Jones and Lee, the significance of contaminants released from dredged sediments, and this would certainly be true for combined sewer overflow as well, must be judged in terms of a critical concentration-duration of exposure relationship for available forms of the contaminant. Available forms are those forms that can have an adverse effect on aquatic organisms. Since some so-called soluble forms are unavailable to aquatic organisms, it is important that the leaching test properly consider available forms of the contaminants of interest. As advocated by Lee and Jones (37) in their November 1978 statement to the Colorado Commission on Water Quality, for interpretation of data such as may be developed from combined sewer overflow leaching tests, the US EPA water quality criteria should be used to flag potential problems. Upon detection of an apparently excessive concentration of contaminants based on US EPA criteria (which were typically developed by chronic expsoure of organisms to 100 percent available forms of contaminants) the source of the contaminant, or in this case the municipalities, would undertake a field study to determine if the contaminants released from the solids as well as those that are present in the aqueous phase of the combined sewer overflow do, in fact, have an adverse effect on water quality, i.e., beneficial uses in the waters receiving combined sewer overflow. Specific guidance can be provided on how municipalities can conduct studies of this type at a minimal cost, which would still provide the necessary information.

Another aspect of the contaminants associated with combined sewer overflow solids that needs to be addressed is that of the direct uptake of these contaminants by benthic and epibenthic organisms which could result in there being a detrimental effect on the organisms or on higher food web organisms, including man who might consume the organisms. The latter area is of particular concern because of the fact that there are a number of chemical contaminants present in combined sewer overflow which would tend to be associated with solids which would cause edible fish and shellfish in the region to become contaminated to the point where they would not be suitable as a source of food for man, based on the Food and Drug Administration limits. These chemicals include mercury, PCB's, and others.

The results of the Dredged Material Research Program and related studies show that one cannot predict, based on the total contaminant content or leachable fraction of contaminants from a particular sediment, the amount of a contaminant that will be taken up directly by aquatic organisms living in contact with these sediments. While there are situations where there is direct transfer of contaminants from these solid phases to the organisms, situations occur [see Neff et al., (38)] where large concentrations of contaminants present in sediments are not transferred to organisms living in contact with them. In fact, organisms may actually be "cleaned up" by the sorption capacity of the sediments, in which the net gradient of the transfer of contaminants is from the organisms to the sediment rather than the reverse.

Jones and Lee (32) have suggested that the appropriate approach to take with respect to dredged material disposal operations where there is concern about the transfer of contaminants from the solids to benthic and epibenthic organisms is to not try to predict such transfer, but to measure whether such transfer is occurring at this time. This can be done by analyzing the tissue of organisms in the vicinity of a disposal site being used to dispose of similar sediments. Therefore, in a similar way studies of organisms from the areas where combined sewer overflow solids are accumulating, would likely show whether or not there are any potential problems from future accumulations of CSO solids in that region. In general, it is important to note that the energetics in terms of hydrodynamic regimes of combined sewer overflow areas are such that periodically the solids of the region would be flushed out or dispersed to deeper or other waters. This is exactly the same situation that occurs in dredged sediment disposal and, therefore, like with the dredged sediment "liquid phase" there is a dilution of the contaminated sediments with lesser contaminated sediments of the region. While dilution does not always result in less contamination of organisms, ultimately since the sediments of many waterways have appreciable sorption capacity for contaminants, it is likely that upon dispersal of the sediments from either dredged sediment or combined sewer overflow, few problems related to the chemical contaminats associated with the CSO solids would likely be encountered.

The Dredged Material Research Program has shown that very little is known today about the effects of contaminants associated with sediments on benthic and epibenthic organisms. It has been well established that many of the contaminants associated with sediments are not available to organisms. However, under certain conditions, there is transfer of contaminants from the sediment. At this time no one is in a position to interpret the significance of the uptake of contaminants to benthic and epibenthic organisms. We do not know the critical body tissue concentrations and therefore we cannot, by analyzing organisms, discern with any degree of reliability the potential impact of a CSO sediment-derived contaminant. As noted above, the only guidelines that are available today in this area are the FDA limits for those organisms which serve as human food. It is unlikely that this situation will change in the foreseeable future and, therefore, the focal point of any contaminant control program for the CSO sediment contaminants must be directed toward edible organisms and those contaminants in which there is a definable limit on critical concentrations, i.e., the FDA limits. It is important that the bulk sediment criteria advocated by some researchers be evaluated before used since these have been clearly shown to be invalid as a basis for predicting adverse effects to benthic organisms. The approach that was developed as part of the Dredged Material Research Program of using bioassays (see

Jones and Lee (32) and Lee et al., (39) for discussion of this area) to detect the problem areas, is a technically valid approach that should be considered. If interpreted properly, bioassays of the type developed by Lee et al., (33), Jones and Lee (32), and Lee et al., (39) can be adapted to the CSO situation to allow municipalities to detect potentially significant problem areas associated with CSO contaminants. Chemical tests will not properly predict organism uptake.

An important aspect of the bioassay program is the proper interpretation of the data. As discussed by Lee et al., (39) the approach used by the US EPA and the Corps of Engineers in their July 1977 bioassay manual may not be technically valid. However, it is being used by a number of environmental quality regulatory agencies. Guidance on the approach that should be used in the interpretation of benthic organism bioassays is provided by Mariani, et al., (40).

It is important to note that the current pollution control efforts of the federal, state, and local agencies will tend to reduce the amounts of highly toxic contaminants entering the combined sewers. The pretreatment requirements for industrial waste will go a long way toward reducing the concentrations of various types of contaminants in combined sewer overflow and, therefore, in time, the environmental impact of combined sewer overflow will become more and more restricted to the physical effects of these solids and the classical pollutants such as oxygen demand and turbidity, associated with domestic wastewaters. Since in general, these effects are of much lesser significance than those of the hazardous chemical contaminants, it is, therefore, important for those who are encountering combined sewer overflow problems to eliminate as soon as possible the "exotic" chemicals entering the combined sewers. Many municipalities have found that by investigating the heavy metal, chlorinated hydrocarbon, and other contaminant content of their domestic wastewaters, they can detect abnormally high concentrations of contaminants which can then be traced back to particular sources and control the source of input. Such a program could readily greatly lessen the environmental impact of combined sewer overflow in many municipal and urban areas.

From an overall point of view, it may be concluded that while no work has been done on the significance of CSO solids as they may cause environmental quality degradation, based on the nature of the materials and the information available from other areas, principally the Dredged Material Research Program, it is apparent that both adverse physical and chemical effects can occur, and that these must be evaluated on a site-by-site basis. Further, the results of the Dredged Material Research Program provide valuable guidance to the approach that should be used in developing a CSO contaminant control program. It is evident that because of the high cost associated with the complete control of combined sewer overflow, careful site-by-site or at least limited-region evaluations should be made by municipalities to be certain that the initiation of such control programs is cost-effective in terms of improving the environmental quality of a particular region that is receiving CSO at this time. There is little point in conducting very expensive programs to control CSO-associated contaminants which are unavailable to affect aquatic life and/or water quality or that have such a limited extent of effect that their elimination would be judged to be essentially inconsequential compared to the cost of their removal. An example of this type of problem occurs with the phosphorus control in the Great Lakes. Sufficient information has been accumulated over the years on the sources and significance of phosphorus in the Great Lakes to enable critical evaluations to be made of the benefits that may be derived by controlling phosphorus from any particular source. One of the potential sources that is of concern is combined sewer overflow. It has been estimated that about five to ten percent of the phosphorus entering Lake Michigan is from combined sewer overflow, Lee (41). While this might be judged to be a significant aspect of the Great Lakes phosphorus control program based on the total phosphorus input, it is apparent that only a small part of the phosphorus associated with combined sewer overflow would be available to adversely affect Great Lakes water quality. Lee et al., (42) have recently completed a comprehensive review of the information available today on the available phosphorus in domestic wastewaters as well as other sources such as urban stormwater drainage. Coincident with developing an understanding of how much of the phosphorus that is present in various sources entering the Great Lakes is likely to become available to stimulate algal growth within these waterbodies, information has been developed on load-response relationships in which it is now possible to predict the impact of altering phosphorus load to one of the Great Lakes, or for that matter, to many other waterbodies based on the results of the OECD eutrophication study that has been conducted over the past several years. Rast and Lee (43), Lee et al., (44), Lee and Jones (45), Jones et al., (46), and Lee et al., (47), have presented the relationships between the reduction in phosphorus loads to each of the Great Lakes and their resulting eutrophication-related water quality. The Lee et al., (44) review has shown that significant reductions in the available phosphorus loads must occur for each of the Great Lakes, especially the lower lakes, if there is to be any improvement in water quality that would be discerned by the public. It is quite apparent that elimination of the combined sewer overflows to Lake Michigan would, even if all of the phosphorus present in the CSO's were avalaible, have little or no impact on Lake Michigan's overall eutrophication-related water quality. When this is considered in light of the fact that upwards of possibly 50 or so percent of the combined sewer overflow would be in a form that would not be available to support algal growth, it is highly questionable whether the control of combined sewer overflow as a means of phosphorus control is cost-effective and technologically valid. As discussed by Lee and Jones (45) there may be situations where control of phosphorus in combined sewer overflow in a particular municipality might, on a localized basis, have a significant beneficial effect on water quality. These situations require a case-by-case evaluation.

It is impossible to generalize on the benefits that would be derived by large-scale combined sewer overflow control. These systems must be examined individually using the techniques available today to assess load-response relationships and availability to contaminants to affect water quality in terms of the typical or normal situations that occur in a particular combined sewer overflow discharge area. It is conceivable that some of the techniques that have been utilized for lake restoration, such as direct iron or alum addition to the lake to control phosphorous might be highly beneficial in eliminating adverse effects of contaminants associated with combined sewer overflow. Lee et al., (42) suggested that the use of water treatment plant alum sludge might be a highly cost-effective means of controlling the impact of urban stormwater drainage on urban waterbodies. It is conceivable that in those areas where it is judged to be too expensive to try to eliminate the combined sewer overflow or to install treatment works, the simple practice of feeding iron or alum to the combined sewer overflow at the time that it is discharged to the environment, including the potential for using wastewater treatment plant sludge, should be investigated. There are few situations in the environment where the addition of a small amount of solids which would occur as the result of allowing the sludge to settle in the receiving waters and thereby carry with it many of the contaminants, would result in a significant environmental degradation. In fact, the high sorption capacity of hydrous metal oxides, such as iron and aluminum (Lee, 48) is such that in many cases the addition of these materials directly to the environment may prove to be highly beneficial in eliminating the problems not only of contaminants present in combined sewer overflow, but also of contaminants derived from other sources as well. It is evident that there is need to investigate the actual environmental impact of combined sewer overflows and to develop guidance that can be used by municipalities to determine for a particular situation, the benefits that can be derived from spending the necessary funds to completely eliminate CSO through combined sewer separation, to treat combined sewer overflows through conventional treatment works, or to partially treat utilizing the environment as part of the treatment system, or from completely failing to do anything about the combined sewer overflow. The ability to provide guidance of this type and to develop systems which are cost-effective, technically valid, and ecologically sound, have improved significantly over the past several years. This improved technology should be brought to bear on the combined sewer overflow problem.

SECTION 4

MODELING THE MOVEMENT OF CSO SEDIMENTS

INTRODUCTION

As discussed in the previous section, the key to determining the impact of CSO sediment material is to determine its fate. The current state-of-the-art of sediment tracing is such that direct measurement is not practical (discussed in Section 5). The most sensible means of determining where CSO sediments come to rest and how they travel is by means of mathematical models.

The purpose of this section of the report is to present an evaluation of a current sediment model for studying the fate of CSO sediments. The model is developed from transport routines in Colorado State University's watershed sediment model. These routines are combined with a flow model developed by the U.S. Geological Survey. The evaluation is designed to determine the facility with which such models might be used to analyze the fate and effects of CSO sediments. A reach of the Cuyahoga River between Akron and Cleveland, Ohio is used in the evaluation. The reach includes the bypass and outfall of the Akron municipal treatment plant. This reach was identified as one in which dissolved oxygen deficits frequently accompany storm events (4).

A brief discussion of the Colorado State University model and the modifications made by Sutron is presented first. This is followed by a complete description of the study reach and the available data. Model calibration and experiments are presented last.

COLORADO STATE UNIVERSITY MODEL AND MODIFICATIONS

Original Watershed Model

As originally configured, the Colorado State University sediment model was designed to predict the sediment yield as a function of time for small forested watersheds. In fact, the original development was funded through EPA with funds from the U.S. Forest Service, Department of Agriculture, Flagstaff, Arizona. The original model is described in reference (49).

The original model simulated the land surface hydrologic cycle, sediment production and water sediment movement. Conceptually, the watershed is divided into an overland flow part and a channel system part. Different physical processes are important for the two different environments. In the overland flow part, processes of interception, evaporation, infiltration, raindrop impact detachment of soil, erosion by overland flow, and overland flow water and sediment routing to the nearest channel are simulated. The overland flow portion was discarded for this study. In the channel system part, water and sediment contributed by overland flow are routed and the amount of channel erosion or sediment deposition through the channel system is determined. The main functions in the original model are shown in Figure 12.

First, the excess rainfall rate is determined by subtracting the interception storage of water by vegetation, the evaporation rate and the infiltration rate from the total rainfall rate. Excess rainfall or the amount of rainfall that runs off the land surface is then routed through the overland flow units downhill to the nearest channel unit. Again, this portion of the model was discarded. Once the water reaches a channel unit, it is routed on to the outlet of the watershed through additional channels based on the principles of continuity and momentum. The amount of sediment transported is governed by the available supply of sediment, transport capacity of the flow of water and the principle of continuity. The continuity (conservation of mass) principle for water and sediment simply states that whatever water or sediment that comes into a stream segment must be either stored there or conveyed out the downstream end in such a way that mass is neither created nor destroyed. The subroutines comprising the channel routing portion of the model were retained and modified for this study.

Model Modifications

Water Routing--

Water routing in the original model predicted the response of the watershed to an input of water which was in the form of excess rainfall. The watershed model printed out the discharge hydrograph at the outlet of the watershed. The water routing formulation was a second-order nonlinear solution of the continuity equation under a kinematic wave assumption. The water routing procedure was also discarded. This was done because the kinematic wave formulation would not work under adverse slope (channel bed elevation increasing downstream) conditions. Such conditions are occasionally formed behind small dams or natural rock outcrops. A linear implicit finite difference flow model developed by Keefer and Jobson (50) was used instead.

The flow model uses a finite-difference solution of the one-dimensional continuity and momentum equations for gradually varied flow. The forms used here are identical to those presented by Amein and Fang (34). The technique used to solve the equations is referred to as fully-forward, linear, implicit. In this scheme, the finite-difference approximations of spatial derivatives are written at the forward time level so that the solution for the unknowns, at the end of the time step, can be obtained without iteration. The linear implicit technique is one of the most stable of the finite difference flow models.

The channel reach to be modeled is represented by a fixed number of grid points up to 100. The channel cross-section at each grid point is

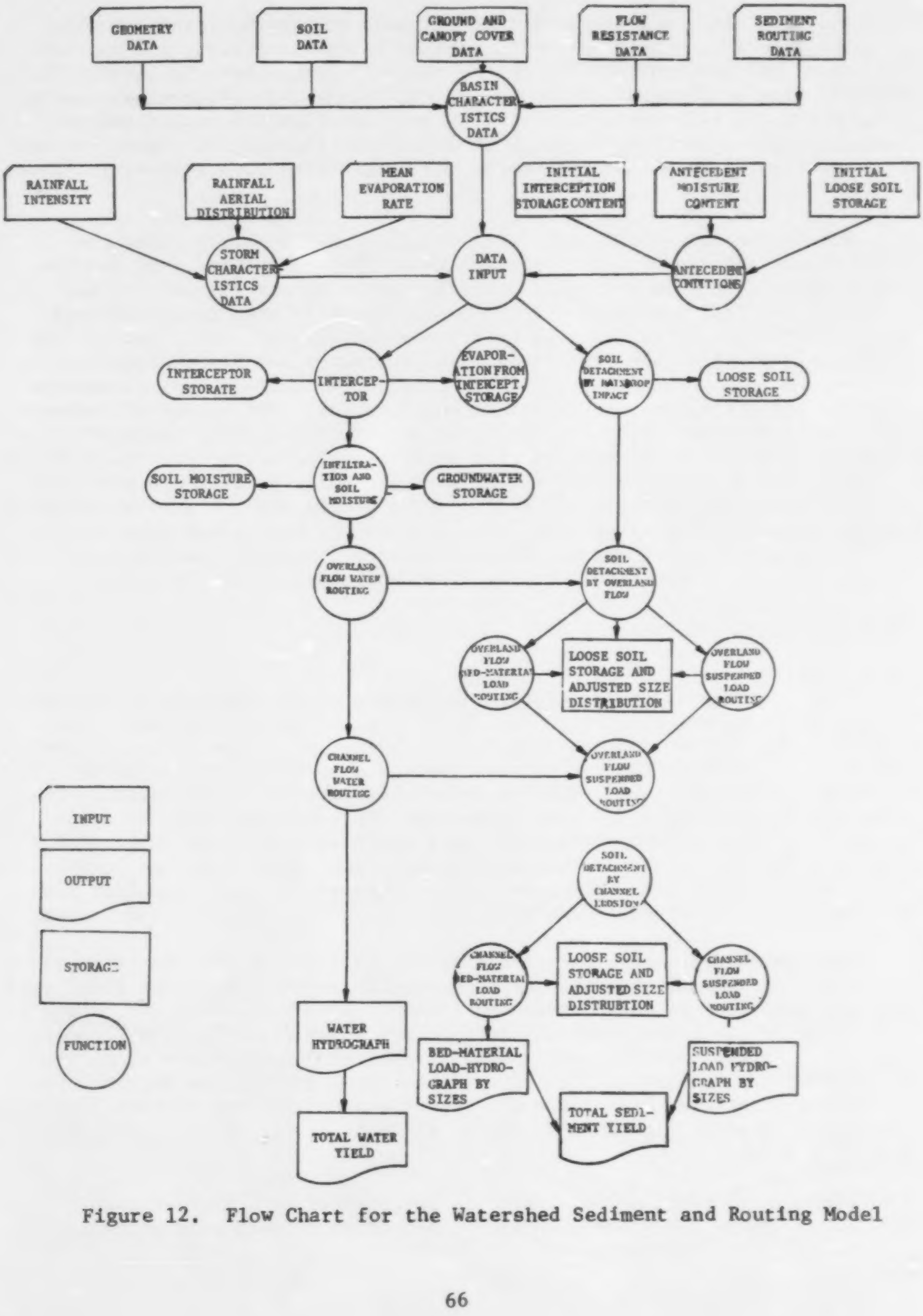
GEOMETRY DATA
SOIL DATA
GROUND AND CANOPY COVER DATA
FLOW RESISTANCE DATA
SEDIMENT ROUTING DATA
BASIN CHARACTERISTICS DATA
RAINFALL INTENSITY
RAINFALL AERIAL DISTRIBUTION
MEAN EVAPORATION RATE
INITIAL INTERCEPTION STORAGE CONTENT
ANTECEDENT MOISTURE CONTENT
INITIAL LOOSE SOIL STORAGE
STORM CHARACTERISTICS DATA
DATA INPUT
ANTECEDENT CONDITIONS
INTERCEPTOR STORATE
INTERCEPTOR
EVAPORATION FROM INTERCEPT. STORAGE
SOIL DETACHMENT BY RAINDROP IMPACT
LOOSE SOIL STORAGE
SOIL MOISTURE STORAGE
INFILTRATION AND SOIL MOISTURE
GROUNDWATER STORAGE
OVERLAND FLOW WATER ROUTING
SOIL DETACHMENT BY OVERLAND FLOW
OVERLAND FLOW BED-MATERIAL LOAD ROUTING
LOOSE SOIL STORAGE AND ADJUSTED SIZE DISTRIBUTION
OVERLAND FLOW SUSPENDED LOAD ROUTING
CHANNEL FLOW WATER ROUTING
OVERLAND FLOW SUSPENDED LOAD ROUTING
INPUT
OUTPUT
STORAGE
FUNCTION
SOIL DETACHMENT BY CHANNEL EROSION
CHANNEL FLOW BED-MATERIAL LOAD ROUTING
LOOSE SOIL STORAGE AND ADJUSTED SIZE DISTRUBTION
CHANNEL FLOW SUSPENDED LOAD ROUTING
WATER HYDROGRAPH
BED-MATERIAL LOAD-HYDROGRAPH BY SIZES
SUSPENDED LOAD HYDROGRAPH BY SIZES
TOTAL WATER YIELD
TOTAL SEDIMENT YIELD

Figure 12. Flow Chart for the Watershed Sediment and Routing Model

represented by up to 20 pairs of elevations and distances. Resistance to flow is set by Manning's "n" value at each cross-section.

The Keefer-Jobson model was used without modification. The program was designed to accept a variety of upstream and downstream boundary conditions as well as tributary flow. Velocities and depths at all model cross-sections can be written on a direct access disc file. The disc file acts as the coupling mechanism between the flow and sediment models. The sediment model reads the velocities and depths rather than computing them as in the original watershed model. An initial run is made with the flow model to predict velocities and depths. The sediment model can then be run with a wide variety of boundary and initial conditions without rerunning the flow model. It should be noted that if substantial changes in cross-section shapes occurred due to aggradation or degradation, direct coupling of the two models would be necessary. Large changes in the bed slope would eventually cause substantial changes in the flow field. For this preliminary evaluation, indirect coupling was considered adequate.

Sediment Transport Routine--

The sediment model will be discussed in greater detail, since it is of primary concern to this study. The sediment routing portion of the model is highly process-oriented. Such fundamental mechanisms of transport such as settling or detachment are handled by a separate equation. The model is believed to be one of the best currently available.

The movement of sediment in a channel is governed by the equation of continuity for sediment and sediment transport equations (such as fall velocity and critical shear stress). The amount of sediment that could be transported is described by equations of sediment detachment by the flow. The equations used in the model are described below.

The equation of continuity for sediment can be expressed as (see reference 51):

$$\frac{\partial G_s}{\partial x} + \frac{\partial CA}{\partial t} + \frac{\partial Pz}{\partial t} = g_s \quad \text{(volume/unit length/time)} \quad (1)$$

Where:

$$C = \frac{G_s}{Q} \quad \text{(volume/volume)} \quad (2)$$

and G_s is the total sediment transport rate by volume, C is the sediment concentration by volume, z is the net depth of loose soil, P is the wetted perimeter, and g_s is the lateral sediment inflow.

The sediment load can be broken into two main categories; bed material load and suspended load. Bed load consists of sediment particles that move by saltation (jumping) or rolling along the stream bed. Suspended load consists of particles that are transported above the bed by the turbulent nature of the flow.

In order to simulate the actual grain size distribution found in soil samples, the sediment load may be broken into any specified numbers of size fractions. The sediment continuity equation is then written using arrayed variables according to sediment size. The percentage of sediment in each size fraction is accounted for in the transport equations.

$$\frac{\partial G_s(I)}{\partial x} + \frac{\partial C(I)A}{\partial t} + \frac{\partial Pz(I)}{\partial t} = g(I) \quad \text{(volume/unit length/time)} \quad (3)$$

in which I indicated which size fraction is being calculated (I = ^{i} number of size fractions, currently limited to 10 in the model).

The sediment transport equations are used to determine the sediment transporting capacity of a specific flow condition. Different transporting capacities are expected for different sediment sizes. The transporting rate of each sediment size can be divided into the bedload transport rate and the suspended-load transport rate. Before a particle can be transported, however, it must be detached from the channel bed. (Note that in all cases, "particle" will refer to spheres with specific gravities of 2.65. The model was subsequently modified to accept other specific gravities, but this will be discussed later.)

When a river flows over its bed, it exerts a tractive force on the bed in the general direction of the flow. This force is called the boundary shear stress and may or may not be large enough to cause sediment particles of various sizes to move. The shear stress at which a given particle begins to move is the critical shear stress. Critical shear stress depends mainly on the specific gravity and diameter of the particle and is given by the following equation:

$$\tau_c = \delta_s(\gamma_s - \gamma)d_s \qquad \text{(force/area)} \qquad (4)$$

Where:

γ_s = the specific weight of sediment
γ = specific weight of water
d_s = particle diameter
δ_s = a constant

The general form of this equation is attributed to Shields, who compared the ratio of gravitational forces holding a particle down to the inertial forces of the flow wanting to carry it away. Analyses comparing the ratio of the energy to cause particle motion and to resist motion given similar results. Laboratory experiments have shown that this beginning of motion criteria is valid for particles with specific gravities from 0.25 up to 8. There is little reason to suspect heavier particles will not also follow this relationship. The constant δ_s has been reported to be 0.06 by Shields (52) and 0.047 by Meyer-Peter and Muller (53).

Shields' critical shear criterion is generally accepted for cohesionless particles from 0.0675 mm sand sizes on up. Sediment which consists of silt and clay particles show greater resistance to erosion than coarser sediment and are not considered in the modes used here.

The critical shear criteria for cohesive sediments are a more difficult problem. A task committee for the American Society of Civil Engineers in the text of their sedimentation manual (54) state the following:

> "The behavior of fine sediments under the attack of flows is complex and depends on many factors including the electrochemical environment of the sediment. Few studies have been made of this problem and knowledge of this phase of sedimentation is therefore in a primitive state."

Despite this, the manual contains some basic information on critical shear criteria of cohesive praticles. Relationships are given based on experimental data that demonstrate that the critical shear stress increases dramatically as the percentage of clay or the plasticity index of the soil in question increase.

Unfortunately, the critical shear stress of cohesive materials depends on such things as the amount of time that the material has been sitting in its present position. The amount of salt content in a clay specimen can change the strength by a factor of 1,000. Such difficulties make the prediction of the critical shear of cohesive materials highly speculative. Use of a given equation that was valid for certain specimens may give tremendously inaccurate results when used in general. Additional research is needed to understand the critical shear and transport of cohesive sediments.

Equations describing the bed load transport generally follows the form given by DuBoys (55) and is closely related to the critical shear stress criteria. These equations often are written as:

$$q_b = a(\tau_o - \tau_c)^b \quad \text{(volume/unit width/time)} \qquad (5)$$

Where:

τ_o = the boundary shear stress acting on a sediment particle
a and b = constants

The boundary shear stress can be expressed by:

$$\tau_o = \frac{1}{8}\rho f V^2 \qquad \text{(force/area)} \qquad (6)$$

Where:

f = a Darcy-Weisbach friction factor due to grain resistance
ρ = the density of water
V = the average flow velocity

Again, numerous engineers have conducted laboratory experiments to determine a and b. A simple and widely used bed load transport equation is the Meyer-Peter, Muller equation (56):

$$q_b = \frac{8}{\sqrt{\rho}\,(\gamma_s - \gamma)} (\tau_o - \tau_c)^{1.5} \quad \text{(volume/unit width)} \qquad (7)$$

where q_b is the bed load transport rate in volume per unit width. A discussion of various bed load equations is found in (55). The Meyer-Peter, Muller bed load equation is incorporated in the model at present but any other formulation could be used if proven more acceptable for the particular type of modeling to be done. Reference (57) gives a complete description of numerous other forumalations and their limitations.

The suspended load plus the bed load gives the total sediment load carried by the stream sediment that is carried in suspension consists usually of smaller sized particles continuously supported by turbulence. Settling velocities for suspended loads are usually quite small.

One of the most widely recognized methods of estimating suspended load was developed by Einstein (58) and was modified by Colby and Hembree (59). The modified Einstein procedure is incorporated in the model and is described below.

The sediment concentration profile which relates the sediment concentration with distance above the bed (49) can be written as:

$$\frac{C_\xi}{C_{a*}} = \left(\frac{R - \xi}{\xi} \; \frac{a*}{R - a*}\right)^w \quad \text{(dimensionless)} \qquad (8)$$

Where:

C_ξ = the sediment concentration at a distance ξ from the bed
C_{a*} = the known concentration at a distance "a*" above the bed
R = the hydraulic radius
w = paramater defined as:

$$w = \frac{V_s}{0.4U_*} \quad \text{(dimensionless)} \qquad (9)$$

Here V_s is the settling velocity of the sediment particles, and U_* is the shear velocity defined as:

$$U_* = \left(\frac{\tau_*}{R}\right)^{1/2} \quad \text{(length/time)} \qquad (10)$$

in which specific shearing stress, τ_*, is defined as:

$$\tau_* = \frac{1}{8} f \rho V^2 \qquad \text{(force/area)} \qquad (11)$$

A logarithmic velocity profile is commonly adopted to describe the velocity distribution of turbulent flow and can be written:

$$\frac{U_\xi}{U_*} = B_1 + 2.5 \ln \left(\frac{\xi}{n_s}\right) \qquad \text{(dimensionless)} \qquad (12)$$

Where:

U_ξ = point mean velocity at a distance ξ above the bed

B_1 = a constant dependent on roughness and n_s is the roughness height

The integral of suspended load above "a*" level in the flow is obtained by combining Equations (8) and (12):

$$q_s = \int_{a*}^{R} U_\xi C_\xi d\xi \qquad \text{(volume/unit length/time)}$$

$$= C_{a*} U_* \int_{a*}^{R} [B_1 + 2.5 \ell_n (\frac{\xi}{n_s})] (\frac{R - \xi}{\xi} \; \frac{a*}{R - a*})^w d\xi \qquad (13)$$

Let

$$\sigma = \frac{\xi}{R} \qquad \text{(dimensionless)}$$

and

$$G = \frac{a*}{R} \qquad \text{(dimensionless)}$$

Substitution into Equation (13) yields:

$$q_s = C_{a*} U_* a* \frac{G^{w-1}}{(1 - G)^w} \left\{ \left[B_1 + 2.5 \ln\left(\frac{R}{n_s}\right) \right] \int_G^1 \left(\frac{1 - \sigma^w}{\sigma} d \right) + 2.5 \int_G^1 \right.$$

$$\left. \ln\sigma \frac{1 - \sigma^w}{\sigma} d\sigma \right\} \qquad \text{(volume/unit length/time)} \qquad (14)$$

According to Einstein (58), the sediment concentration near the bed layer C_{a*} is related to the bed load transport rate q_b as:

$$q_b = 11.6\ C_{a*} U_* a \qquad \text{(volume/unit width)} \qquad (15)$$

in which a is redefined as the thickness of the bed layer which is twice the size of the sediment.

The average flow velocity V is defined by the equation:

$$V = \frac{\int_o^R U_\xi d\xi}{\int_o^R d\xi} \qquad \text{(length/time)} \qquad (16)$$

Using Equation (12):

$$\frac{V}{U_*} = B_1 + 2.5\ \ln\left(\frac{R}{n_s}\right) - 2.5 \qquad \text{(dimensionless)} \qquad (17)$$

Einstein (41) defined the two integrals in Equation (14) as:

$$J_1 = \int_G^1 \left(\frac{1-\sigma}{\sigma}\right)^w d\sigma \qquad \text{(dimensionless)} \qquad (18)$$

and

$$J_2 = \int_G^1 \left(\frac{1-\sigma}{\sigma}\right)^w \ln\sigma d\sigma \qquad \text{(dimensionless)} \qquad (19)$$

The intervals J_1 and J_2 cannot be integrated in closed form for most values of w so a numerical method of determining J_1 and J_2 developed by Li (49) is adopted in this study.

Substitution of Equations (15), (17), (18), and (19) into Equation (14) yields the expression given by Simons et al., (37):

$$q_s = \frac{q_b}{11.6} \frac{G^{w-1}}{(1-G)^w} \left[\left(\frac{V}{U_*} + 2.5\right) J_1 + 2.5\ J_2\right] \qquad (20)$$

(volume/unit width)

The total sediment load per unit width is:

$$q_t = q_b + q_s \qquad \text{(volume/unit width)} \qquad (21)$$

and the sediment transporting capacity of the section G_c is:

$$G_c = Pg_t \qquad \text{(volume/time)} \qquad (22)$$

When considering transport by different sizes, Equation (22) should be modified as follows:

$$G_c(I) = PF_a(I)\ q_t(I) \qquad \text{(volume/time)} \qquad (23)$$

in which $F_a(I)$ is the adjusted fraction of sediment in the ith size.

The percentage in each size fraction on the surface changes over time due to armoring. The water transports the smaller sizes more easily and leaves the larger size fractions behind. Thus, the percentages of surface material need adjustment each time step. If the total loose soil depth is greater than D_{84} (the size of sediment for which 84% of the sample is finer), the adjusted percentages, $F_a(I)$ can be written as:

$$F_a(I) = \frac{Z(I)}{\sum_{I=1}^{M} Z(I)} \qquad \text{(dimensionless)} \qquad (24)$$

If the total loose soil depth $\sum_{I=1}^{M} Z(I)$ is less than D_{84}, then the adjusted percentages must account for the layer of undisturbed soil which is distributed according to the original percentages plus the loose soil which covers it.

$$F_a(I) = \frac{1}{D_{84}} \left\{ Z(I) + F(I) \left[D_{84} - \sum_{I=1}^{M} Z(I) \right] \right\} \qquad (25) \ \text{(dimensionless)}$$

Often a size class or type of sediment particle is not found initially in the bed material but is tranported into the reach of the water flowing in the channel. For example, the transport of heavy metals in a CSO may affect size distribution in the bed. In this situation, the percentages of incoming material into a channel reach are used to further modify the adjusted percentages of size classes found in the bed. This modification was added by Sutron as part of this study.

The amount of sediment detachment from surface bed runoff is determined by comparing the sediment transporting capacity of the total available amount of loose soil. By substituting the sum of the transporting capacities, $\sum_{I=1}^{M} G_c(I)$, (given by summing the transport rates for M size fractions) into the transporting rate given by Equation (1), the total potential changes in loose soil storage is determined:

$$\Delta Z^P = \frac{\partial Z^P}{\partial t} (\Delta t) \qquad \text{(length)} \qquad (26)$$

If $\Delta Z^P \geq -Z$, the loose soil storage is enough for transport and no detachment of soil by surface runoff is expected. Soil is detached if $\Delta Z^P < -Z$ and the amount of detachment is:

$$D = -D_f[\Delta Z^P + Z] \qquad \text{(length)} \tag{27}$$

in which D is the total amount of detached soil and D_f is defined as a detachment coefficient with values ranging from 0.0 to 1.0 depending on soil erodibility. As an example, if the flow were over a nonerodible surface, the value for D_f would be zero. If one were considering flow in a river where the riverbed is always loose, the value for D_f would be unity.

The new amount of loose soil should be further modified as follows:

$$Z(I) = Z(I) + D[F(I)] \quad \text{(length)} \tag{28}$$

in which Z(I) is calculated for each size fraction of sediment. The numerical procedure used for sediment routing is now presented. The transporting capacity is determined by using Equation (23) and the computed flow conditions from the water routing model. The potential sediment load concentration for a given size fraction is then:

$$C^P{}_{(I)} = \frac{G_c(I)}{Q_{j+1}^{n+1}} \qquad \text{(volume/volume)} \tag{29}$$

These qualities are at time n + 1 and space j + 1 in the space-time plan. When computing the potential sediment transport, the excess shear may be less than or equal to zero indicating that at that section of channel that particular sediment particle will settle out. Even though the excess shear is negative, some particles may be transported downstream because their settling time may be too slow as compared with the time it takes the particle to move downstream at the average stream velocity. Thus, a certain minimum transport rate is maintained for that particular class of particles. This minimum rate may be near zero when settling velocities are large enough. This capability was also added to the model by Sutron as part of this study.

The potential change in loose soil storage for sediment in a given size fraction is:

$$\begin{aligned} \Delta Z^P(I) = \frac{1}{P} \Big\{ G_s(I)\Delta t - \theta \Big[\Big(C^P(I) Q_{j+1}^{n+1} - G_s(I)_j^{n+1} \Big) (1 - a) \\ + \Big(G_s(I)_{j+1}^n - G_s(I)_j^n \Big) a \Big] - \Big(C^P(I) A_{j+1}^{n+1} - C(I)_{j+1}^n A_{j+1}^n \Big) \\ (1 - b) + \Big(C(I)_j^{n+1} A_j^{n+1} - C(I)_j^n \, A_j^n \Big) (b) \Big] \Big\} \end{aligned} \tag{30}$$

(length)

If $\Delta Z^P(I)$ is positive, that size of sediment is aggrading on the bed; and if negative, that size of sediment is being transported off the bed.

The actual transport rate depends on both the availability of material and the transporting capacity of the flow. If $\Delta Z^P(I) \geq -Z(I)$, the availability is greater than the transporting capacity. Thus, the transport rate for material in size fraction I is equal to its transporting capacity or:

$$C(I)_{j+1}^{n+1} = C^P(I) \qquad \text{(volume/volume)} \qquad (31)$$

and the actual change in Z(I) is:

$$\Delta Z(I) = Z^P(I) \qquad \text{(length)} \qquad (32)$$

If $\Delta Z^P(I) < -Z(I)$, the availability of material is less than the transporting capacity. The transport rate is limited by the availability of loose soil and the bed material concentration is therefore:

$$C(I)_{j+1}^{n+1} = \Big\{\Big[\Big(C(I)_{j+1}^{n} A_{j+1}^{n} (1 - b) - C(I)_{j}^{n+1} A_{j}^{n+1} - C(I)_{j}^{n} A_{j}^{n}\Big) (b)\Big] + g(I)\Delta t - \theta \Big[-G_s(I)_{j}^{n+1} (1 - a) + \Big(G_s(I)_{j+1}^{n} - G_s(I)_{j}^{n}\Big) (a)\Big] + PZ(I)\Big\} \Big/ \Big\{A_{j+1}^{n+1} (1 - a) + \theta\, Q_{j+1}^{n+1} (1 - a)\Big\} \qquad \text{(length)} \qquad (33)$$

and

$$\Delta Z(I) = -Z(I) \qquad \text{(length)} \qquad (34)$$

The sediment transport rate $G(I)_{j+1}^{n+1}$ is determined by Equation (2):

$$G(I)_{j+1}^{n+1} = C(I)_{j+1}^{n+1}\, Q_{j+1}^{n+1} \qquad \text{(volume/time)} \qquad (35)$$

and the amount of loose soil available at the next time increment is:

$$Z(I) = Z(I) + \Delta Z(I) \quad \text{(length)} \qquad (36)$$

A four point noniterative finite difference scheme is used to solve the above equations at each cross-section at each time step. This concludes the presentation of the model theory. The following section describes the Cuyahoga River study reach where the model was tested.

CUYAHOGA RIVER STUDY REACH

General Considerations

The river reach selected for this study is illustrated in Figure 13. The figure is taken from reference (60). The reach extends from the U.S. Geological Survey guying station, "Cuyahoga River at Old Portage" downriver to the Cuyahoga Estuary at Lake Erie. A straight line distance of slightly over 40.23 km (25 miles) is involved. The distance along the river is 64.37 km (40 miles) counting meanders.

Reasons for Selecting Reach

Two basic reasons for selecting this study reach were data availability and a history of water pollution problems. The USGS stream gauges at Old Portage and Independence have been in existence for many years. Four parameter water quality monitors (DO, pH, temperature, and conductivity) are also maintained at both gauges. Most important for this study, sediment samples had been collected at both gauges by continuous pumping samplers. The Akron sewage treatment plant is located 4.83 km (3 river miles) below the Old Portage gauge. An additional stream gauge, "Cuyahoga River at Ira," is located close below the treatment plant outfall. Records from the USGS gauges provided most of the data necessary to develop the sediment model.

The Cuyahoga estuary is widely known for having caught fire in the 1960's. In a previous study [EPA Contract No. 68-03-1630 (4)], Sutron identified the study reach as one in which a high probability existed for DO deficits to occur at times of urban storm runoff.

General Characteristics of Basin and River

A good general description of the runoff and sedimentation characteristics of the Cuyahoga basin is contained in (60). The Cuyahoga River Basin lies in northeastern Ohio and drains an area of about 810 square miles. There is a breakwater protected outer harbor at Cleveland of about 526 hectares (1,300 acres) and the 9.33 km (5.8 miles) of channel near the mouth have been improved for navigation. The basin contains portions of the cities of Akron and Cleveland and is one of the most heavily industrialized areas in the United States. The basin has a humid climate with precipitation distributed fairly uniform throughout the year. Mean monthly precipitation values at Cleveland vary from a minimum of 5.92 cm (2.33 inches) in February to a maximum of 8.86 cm (3.49 inches) in May. The average annual precipitation

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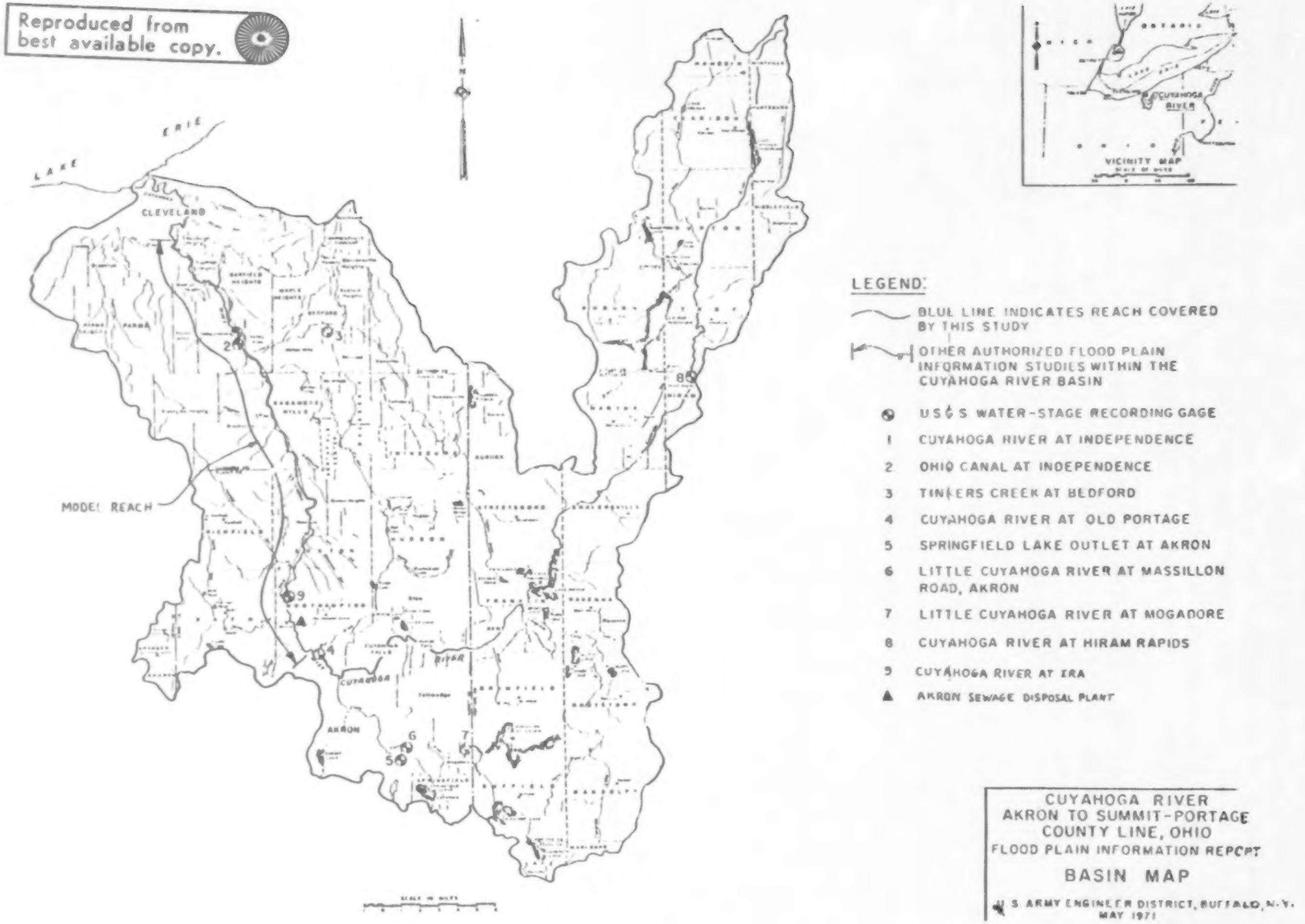
LAKE ERIE
CLEVELAND
MODEL REACH
CUYAHOGA RIVER
AKRON
N
VICINITY MAP
LEGEND:
BLUE LINE INDICATES REACH COVERED BY THIS STUDY
OTHER AUTHORIZED FLOOD PLAIN INFORMATION STUDIES WITHIN THE CUYAHOGA RIVER BASIN
USGS WATER-STAGE RECORDING GAGE
1 CUYAHOGA RIVER AT INDEPENDENCE
2 OHIO CANAL AT INDEPENDENCE
3 TINKERS CREEK AT BEDFORD
4 CUYAHOGA RIVER AT OLD PORTAGE
5 SPRINGFIELD LAKE OUTLET AT AKRON
6 LITTLE CUYAHOGA RIVER AT MASSILLON ROAD, AKRON
7 LITTLE CUYAHOGA RIVER AT MOGADORE
8 CUYAHOGA RIVER AT HIRAM RAPIDS
9 CUYAHOGA RIVER AT ERA
▲ AKRON SEWAGE DISPOSAL PLANT
CUYAHOGA RIVER
AKRON TO SUMMIT-PORTAGE COUNTY LINE, OHIO
FLOOD PLAIN INFORMATION REPORT
BASIN MAP
U.S. ARMY ENGINEER DISTRICT, BUFFALO, N.Y.
MAY 1971

Figure 13. Model Reach

at Cleveland, based on a 96-year period, is 89.31 cm (35.16 inches). A large portion of the basin has been urbanized and the average population density is about 115 persons per square kilometer (300 per mile^2). Flood peaks near the mouth resulting from rainfall over the entire basin occur principally as a result of runoff from the downstream portion of the basin. In recent years, runoff above Old Portage has contributed only 10 to 20 percent of the maximum discharges recorded in the downstream basin.

Streamflow in the Cuyahoga River Basin follows a characteristics seasonal pattern. Fall and winter flows are generally low. There is a marked rise in discharge during March and April by runoff from the winter's melting snowpack and ice cover. Runoff is normally well sustained during April, May, and June. During late summer the streamflow is quite low. Heavy rains may cause sharp rises during any of the spring, summer, and fall months. Flows at Independence have varied from a minimum of 0.4 m^3/sec (14 cfs) on November 30, 1930 to a maximum of 701.8 m^3/sec (24,800 cfs) on January 22, 1959. The average annual runoff from the basin upstream from the gauge is about 34.56 cm (14 inches).

In 1952 the Department of Agriculture made a study of the erosion and sediment damage which occurs in the Cuyahoga River watershed. The results of the watershed study shows that 28.1 percent of the total sediment reaching Cleveland Harbor comes from a stream bank erosion; 15.5 percent is contributed by sheet erosion; 8.1 percent comes from flood plain scour, and 0.3 percent is from valley trenching and gully erosion. The remaining 48 percent was estimated to be supplied by municipal and industrial CSO wastes. The Department of Agriculture study also showed that 6.5 percent of the total sediment load upstream from the harbor originated as industrial and domestic waste. Presumably, some of all or this would have to originate at Akron and the small towns in between.

Supplemental Data

Some field data were required to develop the sediment model. These data include information on the nature of the sediments in the study reach and descriptions of the river cross sections.

A field trip was conducted during the last week of November 1978 to obtain the required data. Sutron personnel traveled to Cleveland and surveyed 11 cross sections of the river at all highway bridges from Old Portage to Independence. At the same time, representative samples of the bed and bank material were collected. On route to Cleveland, the USGS office in Columbus, Ohio, was visited and published flow and sediment data obtained. While in Cleveland, the U.S. Corps of Engineers was contacted and a number of additional river cross sections obtained for the reach of the river below Independence into Cleveland Harbor. Operating personnel at the Akron sewage treatment plant were contacted. They indicated that little was known about the sediment load from their outfall, particularly at times of high flow. Turbidity records were available but these were considered to be of little value. The plant operators indicated that bypassing of the plant was not uncommon during wet weather. Bypassing activities resulted in sizable quantities of raw waste being dumped in the river. Holding ponds were under construction to help alleviate this problem.

Modeling Program Overview

It was realized from the outset that an absolutely accurate model of the Cuyahoga could not be developed with the available budget. The objective was to create a reasonable model which could be used to assess the capability to predict the fate and effects of CSO sediments. In this case, the CSO resulted from the bypassing of the Akron treatment plant at as many as 37 overflow plants.

The modeling program proceeded through a series of distinct stages. The first step was to analyze the field data and create a flow model of the study reach. Next, several velocity-depth files were created for use in the sediment model. Finally, a number of experiments were conducted with the sediment model.

Initial sediment model experiments concentrated on determining if it was possible to figure out where sediment material from the Akron plant would deposit. Next, experiments were conducted to determine how the deposits moved under unsteady flow conditions. Finally, experiments were conducted to determine how particles with specific gravities other than that of sand (2.65) would move down the river. The flow and sediment modeling efforts will be described in detail in the following sections.

Flow Model

The writer's experience indicated that the first step in developing a successful unsteady flow model is to obtain successful backwater (steady flow) profiles of the study reach. The velocities and depths from these study flow calculations are from the initial conditions for the unsteady flow model. Areas of possible instability in the unsteady flow model can usually be identified by careful examination of the steady flow profile for anomalous depths or unusually high velocities.

The cross section information gathered by Sutron was combined with the data from the Corps of Engineers to create a complete bed profile of the Cuyahoga from Old Portage to the estuary. When cross sections were widely spaced (greater than 3 miles) additional sections were interpolated. A stable, reasonable appearing backwater profile was obtained using 29 cross sections at from 0.4 to 3.22 km (1/4 to 2 miles) spacing. Two profiles for 3.54 and 25.5 m^3/sec (125 to 900 cfs) are illustrated in Figure 14. These flow values were typical of those observed during the summer.

The three most significant features of the backwater profile are the two small impoundments at 16.1 km and 30.6 km (10 miles and 19 miles) below Old Portage plus the estuary which begins at 46.7 km (29 miles). These areas of increased depth and lower velocity act as sediment traps and are very important in considering the fate of sediment materials from the STP, as will be seen shortly.

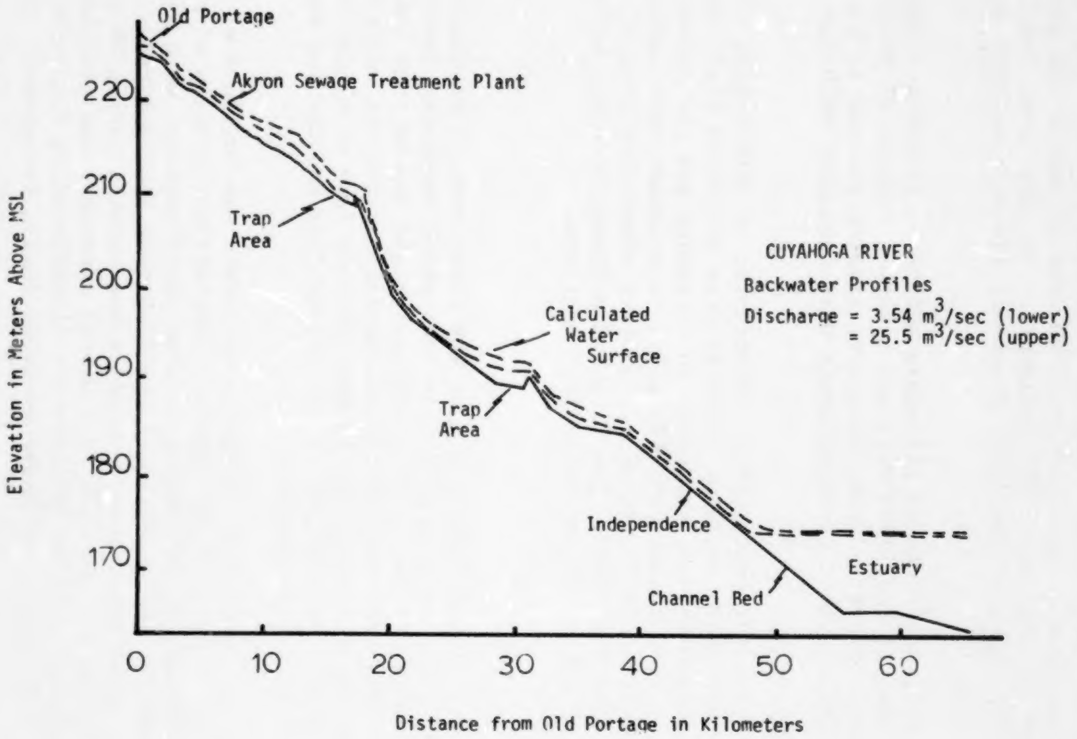

Figure 14. Steady Flow Water Surface Profiles

With steady flow established, the next step in developing the flow model was to select a period of historic record for use in calibration and testing. A period was selected from the summer of 1976. Sutron had processed a month of hourly flow and dissolved oxygen data for both Old Portage and Independence for this time period as part of an earlier study. This period of record for the gauge at Old Portage is illustrated in Figure 15. Discharge only for the same time period at both Old Portage and Independence is illustrated in Figure 16. The period selected for use in the model is shown on both figures. There were two reasons for selecting this time period. First, sizable DO deficits occurred at Independence at the time of the small hydrograph peaks. The writers wished to examine the sediment discharge at that time. Second, the much larger hydrographs beginning on the 22nd day exceeded bank fill stage. This was beyond the range of the surveyed cross sections. An additional advantage of this time period was the period of nearly steady flow from day 14 onward. This meant that the reach was nearly in equilibrium which is what was assumed for model initial conditions.

Additional discharge information was required to complete the flow model. The flow from the Akron STP was required as well as the tributary inflow from Tinkers Creek, a large stream which enters above the Independence gauge. Estimates of these flows were obtained from USGS daily flow records. Figure 17 illustrates the daily average flow at Old Portage, Ira, and Independence, as well as the discharge from Tinkers Creek and the sediment flow at Old Portage. The difference in flows between Old Portage and Ira was used as the treatment plant outflow. This is quite reasonable as no major tributaries other then the STP outfall enter the Cuyahoga in that reach and no bypasses occurred during the model period. The use of the sediment data will be explained later.

The very steep reach between kilometer 16.1 and 32.2 (miles 10 and 12) as well as the sharp breaks in slope at the small control structures required small time stages in the flow model. One half hour was used with good results. All flow values were interpolated to this time increment for use as input data.

No great effort wasmade to calibrate the flow model. The daily average values from Tinkers Creek filtered out all detail. A number of other sizable tributaries as well as withdrawal points occurred in the reach. No data from these were available. A comparison was made, however, to see that the predicted stage changes at Independence were reasonable. The results of this comparison are illustrated in Figure 18. Also illustrated on the figure is the dissolved oxygen level and the saturation dissolved oxygen level plus the predicted sediment load. The figure indicates that the predicted stage variations are at least reasonable, if not perfect. The inability of the model to predict the second small rise in stage is felt to be due to the absence of hourly data from Tinkers Creek (that is, real hourly data, not the one-half hour interpolated values). The sediment and dissolved oxygen values will be discussed later.

After the flow model was successfully developed, it was desired to have a larger size hydrograph for use in the sediment model. The idea was to determine what magnitude of flows might cause sediment deposits at the outfall

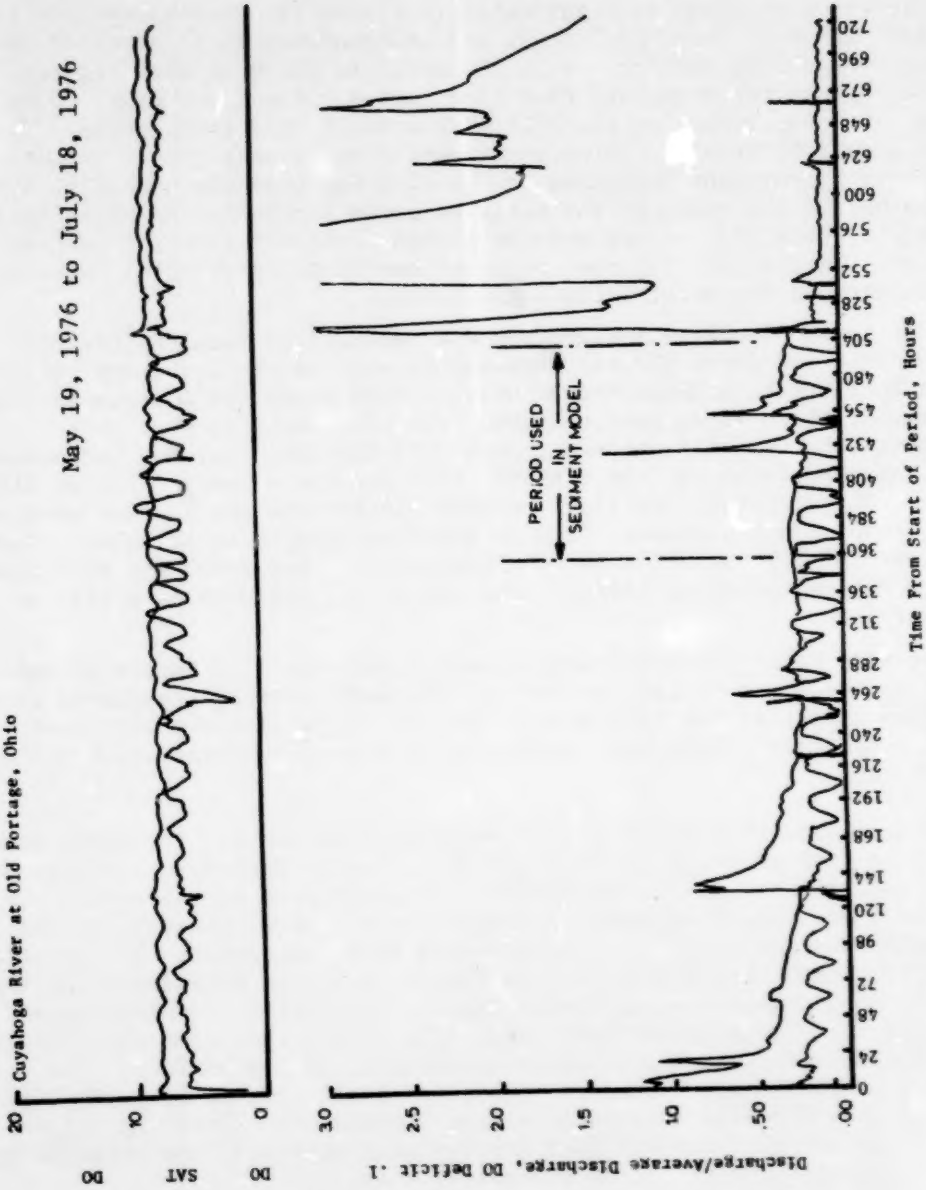

Figure 15. Hourly Discharge and DO Data at Old Portage

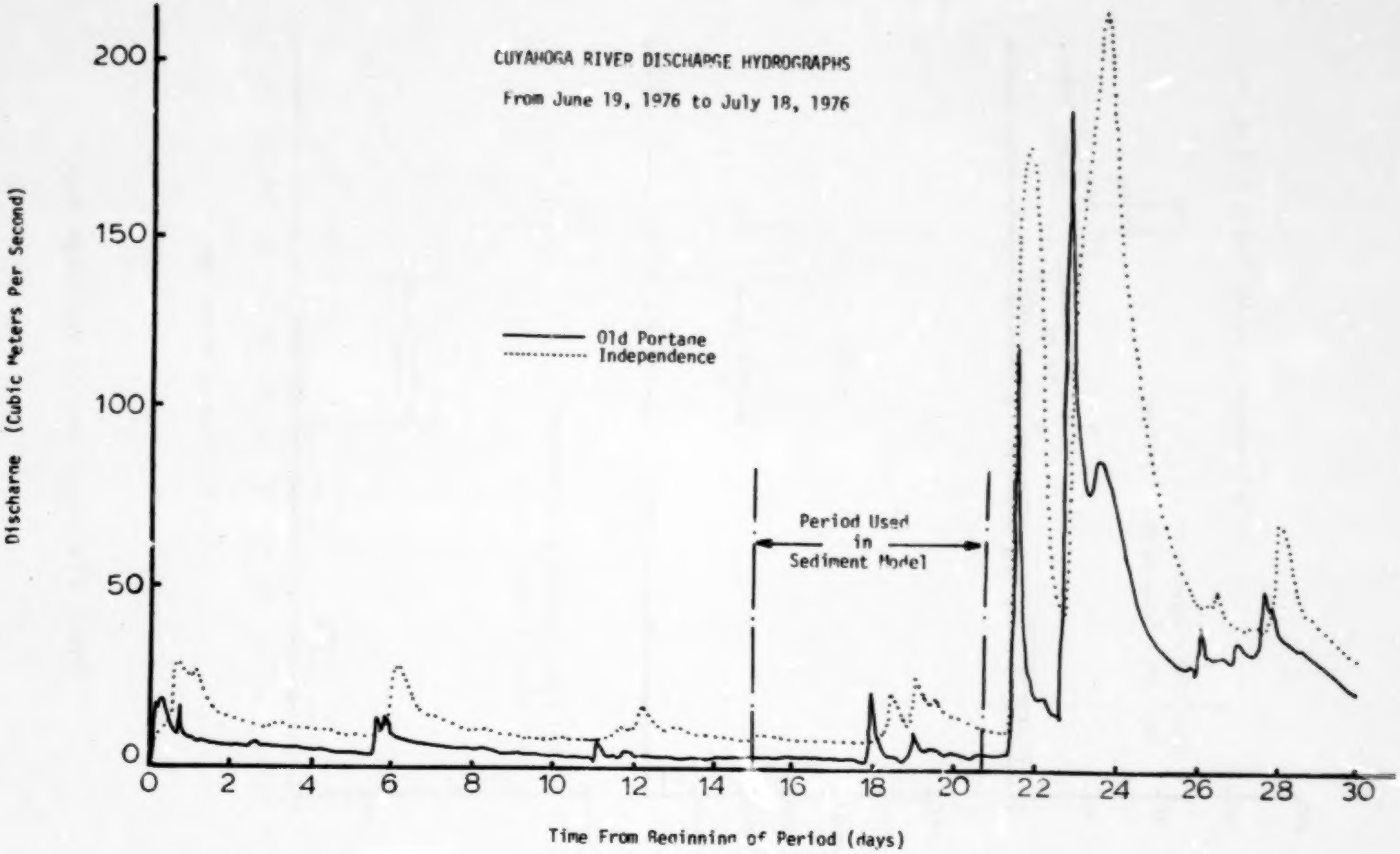

Figure 16. Cuyahoga River Discharge Hydrographs from June 19, 1976 to July 18, 1976

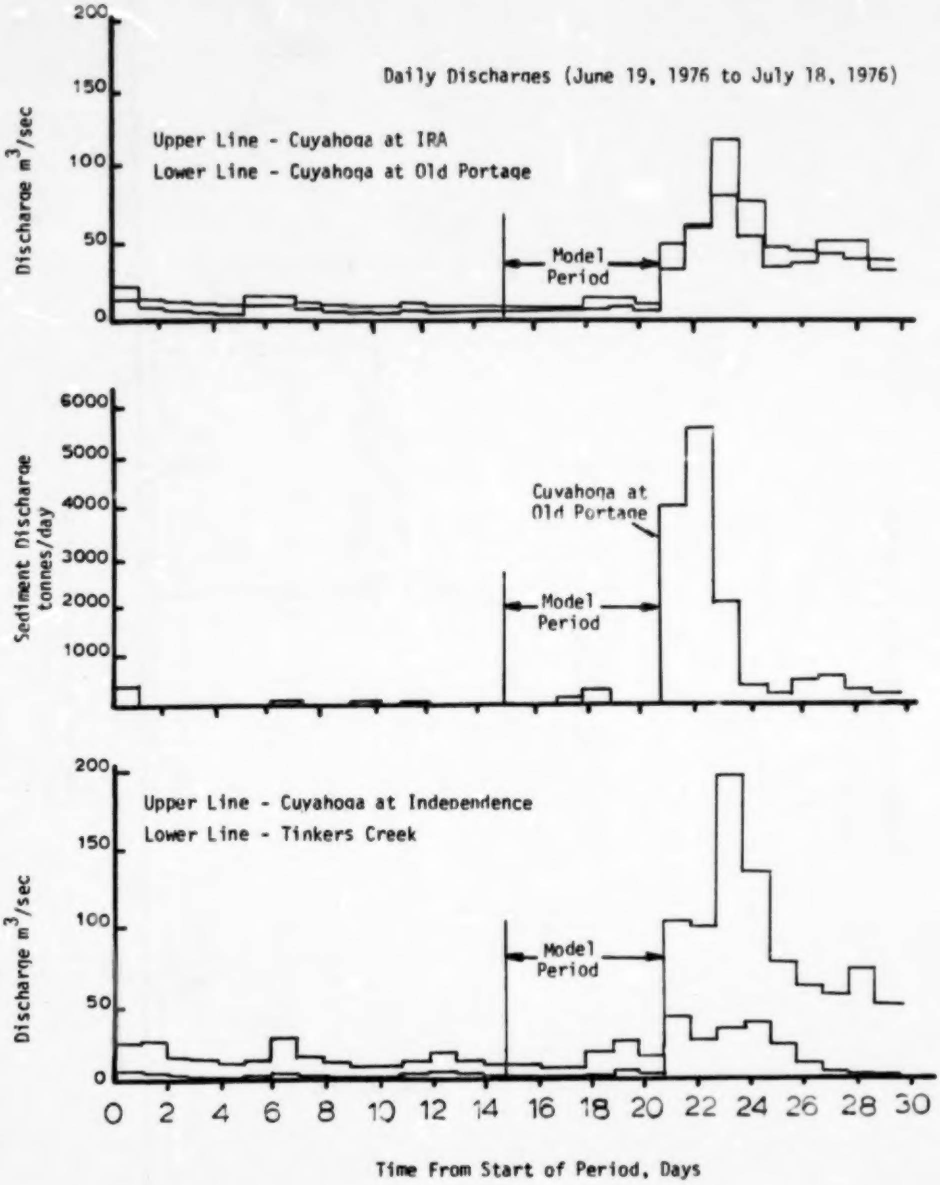

Figure 17. Supplemental Discharge Data

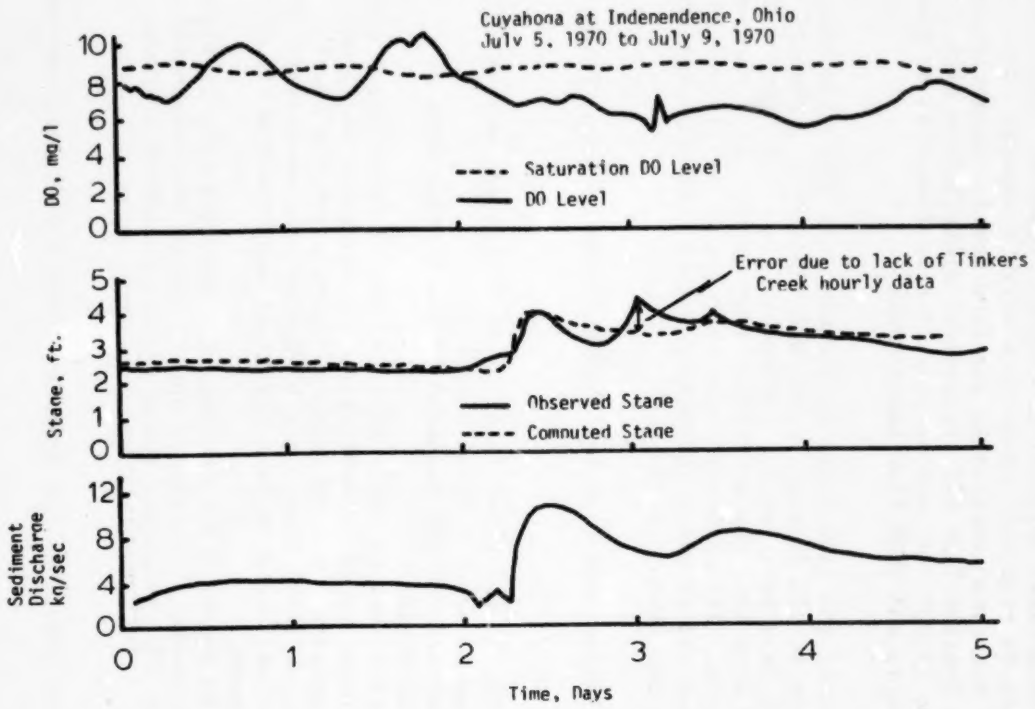

Figure 18. Dissolved Oxygen, Flow, and Sediment at Independence

and other locations to be reentrained and move on downstream. In order to select a reasonable hydrograph, a simple flood frequency analysis was run on the daily average maximum flows at Old Portage. This analysis is illustrated in Figure 19.

Initially, two peak flows were selected. These were 84.95 m^3/sec (3,000 cfs) with a recurrence interval of roughly five years and 127.4 m^3/sec (4,500 cfs) with a recurrence interval of roughly 50 years. Unfortunately, the 50-year flow exceeds bank full stage by a sizable margin. This exceeded the capabilities of the cross section in the flow model. An artificial hydrograph based on Pearson Type III statistical distribution with a peak flow of 84.95 m^3/sec (3,000 cfs) and an overall time from rise to recession of 48 hours was used in the high flow experiments.

The net results of the flow model development was disc file containing velocities and depths at all 29 model cross sections for a period of 8-1/3 days. The first six days were "real," representing the calibration data. The remaining 2-1/3 days were the artificial hydrograph with a recurrence interval of five years. The philosophy was that a qualitative determination could be made of when and to where sediment deposits formed during the "real" period moved during the five-year flood.

Some general observations from the flow modeling portion of the study are:

--The bed profile of the river is of great importance and should be established as accurately as possible.

--Major manpower efforts are required to obtain flow data at small time intervals.

--If steep reaches such as below mile ten are of interest, a revised backwater program would be desirable. Considerable difficulty was encountered getting the flow model to start correctly there because of superficial flow. The backwater program used in this study assumed all flows to be subcritical and computed all profiles working upstream.

--Other than the above, the technology for modeling flow is highly developed and reasonably easy to apply. Costs are reasonable, being roughly $25 to $40 for the 8-1/3 day period of 1/2 hour values.

The following section describes the sediment model development and experimental results.

Sediment Model

Model Setup--

The biggest single difficulty encountered with the sediment model was lack of information. A great deal had to be assumed or calculated based on reasonable guesswork.

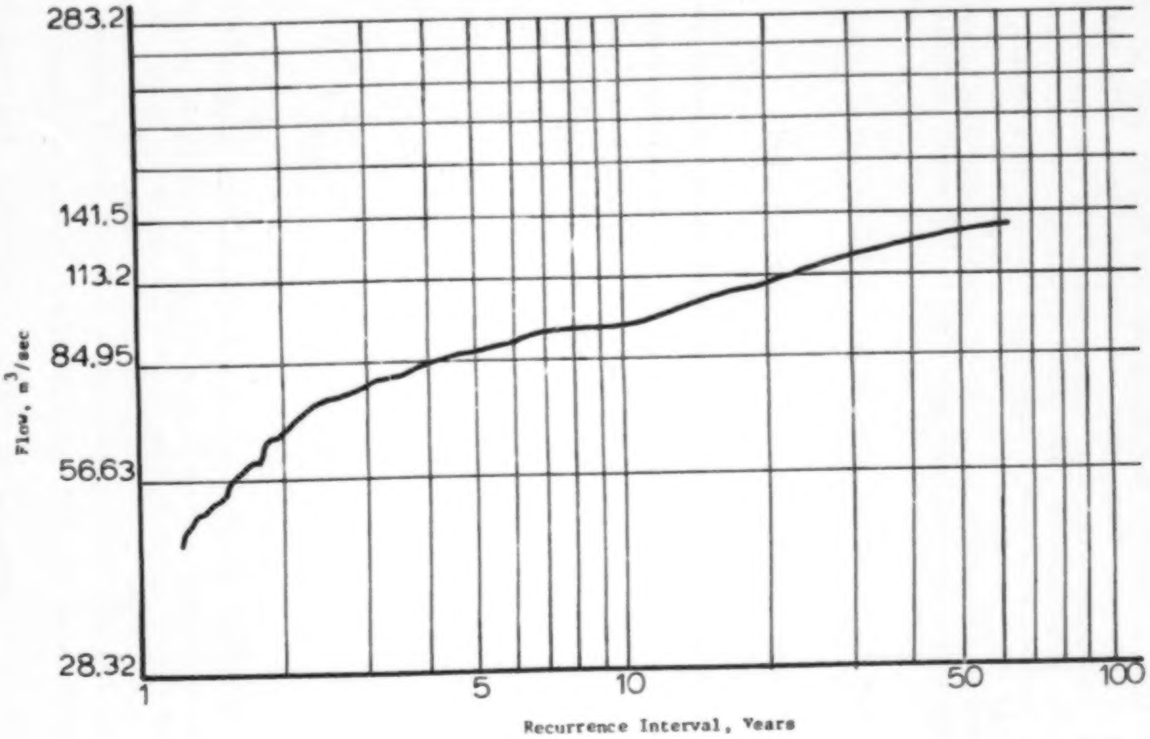

Figure 19. Flood Frequency Data, Cuyahoga River at Old Portage
(Annual Average Maximum Daily Flow)

The sediment model required much the same information as the flow model plus additional information on sediment inflows. The stream bed profile and cross section information were available from the flow model, as well as the disc file of velocity and depth data. The sediment inflow was developed from USGS data and from information presented in Section 6.

The sediment inflow at the Old Portage gauge was fairly easy to obtain. This was plotted in Figure 16. There were two disadvantages. The data were daily averages and only total load was given. Only isolated samples were analyzed for size distribution. The model required 1/2-hour inputs of sediment in each desired size class (six size classes were used). These two disadvantages were overcome by developing six sediment rating curves. A year of daily sediment discharges was plotted versus daily discharges. This gave a total suspended load rating curve (note that since no bed load data were available, the suspended load was assumed to be the total load).

Table 21 from USGS analysis lists the distribution of sizes found in the suspended load.

TABLE 21. SIZE DISTRIBUTION OF SUSPENDED SEDIMENT LOAD AT OLD PORTAGE

Sieve Size, mm	Percent	Classification
Less than .002	35	CLAY-SILT
.002	7	
.004	9	
.008	13	
.016	13	
.031	5	↓
.062	7	SAND
.125	11	↓

These data were used to develop rating curves for each size class by multiplying the total load rating curve by the percentage in each class. In the model, no sieve size larger than 0.062 was used. Thus, 89 percent of the total load was assigned to the 0.62 mm and smaller sizes and 11 percent was carried in the geometric mean of .062 and .125 size classes ($0.18 \text{ mm} = \sqrt{.062*.125}$).

The sediment model also required an initial condition. This was the percentage of sediment present in each size class at each model cross section. These data were obtained from the sediment samples collected by Sutron. Since the samples were few and widely scattered, they were all averaged and the same size distributions used at all cross sections. Table 22 lists the values used. In the absence of actual data, the size distribution of the sediment material from the treatment plant had to be estimated Based on the data from Section 3, District of Columbia street solids were selected as typical. Table 23 lists the percentages which were assigned to the sediment from the Akron STP.

TABLE 22. DISTRIBUTION OF SIZES IN BED SEDIMENT

Size Class, mm	Percent Assigned to Class	Classification
.063	.52	SAND
.180	1.07	
.350	3.97	
1.770	12.78	
7.070	40.00	GRAVEL-COBBLE
100.000	41.66	

TABLE 23. DISTRIBUTION OF SIZES IN AKRON STP FLOW

Size Class, mm	Percent Assigned to Class	Classification
.063	28	SAND
.180	20	
.135	37	
1.770	15	

The important thing to note about the three size distributions is their sizable difference. The upstream inflow is virtually all fine material. The inflow from the treatment plant is primarily sand (remember, this is hypothetical). The channel bed is primarily gravel and cobble sizes.

The method of determining the quantity of sediment discharges from the treatment plant should be mentioned. The data in Section 3 indicated that a concentration of 589 mg/ℓ is typical of CSO solids. The STP flows (Cuyahoga at Ira minus Cuyahoga at Old Portage, Figure 16) were mulitplied by this concentration times the appropriate percentage and converted to pounds per second inflow. At the end of the calibration flow (six days) the sediment flow from the STP was held constant. A worthwhile program modification would be a sediment rating curve for the STP flow.

One of the most unfortunate aspects of the entire study was the lack of sediment outflow data from the study reach. Initial conversations with the USGS left the impression that sediment data were collected at both Old Portage and Independence. They are, but unfortunately not in the same year. This made it impossible to calibrate the sediment transport rate.

CSO Sediment Transport Experiments--

Normal sediment experiments--

The initial experiments performed with the sediment model were to determine if the model could distinguish between sediment deposits resulting from the STP flow and deposits resulting from the natural sediment flow at Old Portage. The results of these experiments are illustrated in Figures 20 and 21. Figure 20 illustrates the deposition and erosion patterns in the channel at three different times with zero sediment flow from the STP. These are at 1,800 minutes (1-1/2 days), 9,000 minutes (6-1/4 days), and 12,000 minutes (8-1/3 days) after the beginning of the model. These times correspond to the end of the period of study flow just prior to the first "real" hydrograph, the time immediately before passage of the 3,000 cfs, five-year flood hydrograph, and the end of the five-year flood hydrograph. Deposition/erosion depths are shown at each cross section for each of the six size classes modeled.

The results indicate that during the steady flow period preceding the hydrographs, no sediment was transported. That is, the solid line coincides with the graph axis. The passage of the "real" hydrograph moved fine material (.063 mm) from the controls for the two small impoundments and the steep slopes downstream. Small amounts of movement occurred at the control points in the 7.07 mm size class. Note that .001 ft. of the degradation is less than one particle diameter and thus is not measurably significant. The passage of the five-year flood results in further erosion in the same location. The higher velocities move the fine material deposits further out into the estuary. In viewing these graphs, recall that virtually all the natural inflow was fine material and the bed material is mostly course.

Figure 21 illustrates the same information as Figure 20 but with sediment inflow from the STP included. The deposit areas for the STP material are easily identified because of the sizes involved. Most of the material was in the .18, .35, and 1.77 mm size classes. Thus, any deposition is due to the STP. The results indicate that prior to the passage of the "real" hydrograph, the STP sediments deposited at the outfall. The passage of the real hydrograph moved some of all the .18 - 1.77 mm material down to the first small retention structure at mile ten. The passage of the five-year flood hydrograph resulted in the .18 mm size class of the STP sediments reaching

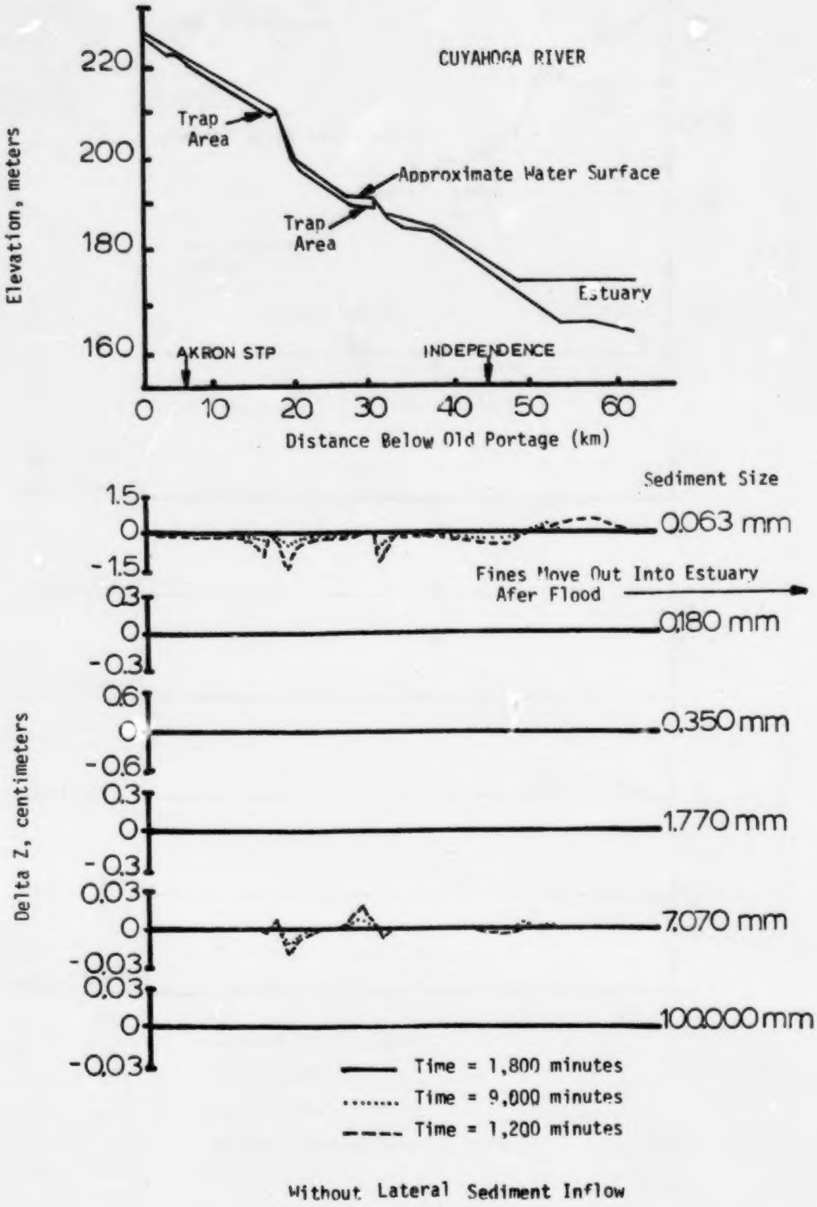

Figure 20.Deposition and Erosion

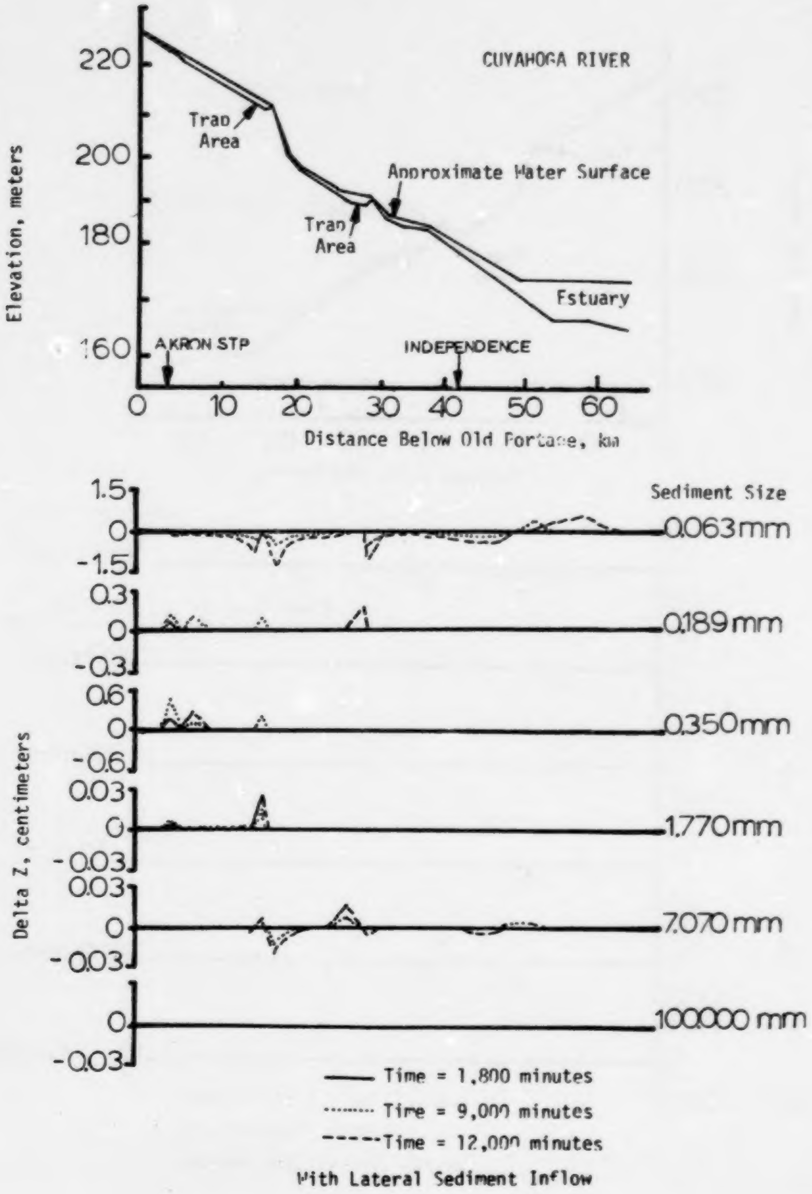

Figure 21. Deposition and Erosion

the second retention structure at mile 20. These experiments indicate that it is qualitatively possible to predict the fate of the STP sediments.

The behavior of the channel bed at the STP outfall for the entire time period of the model is illustrated in Figure 22. Shown in the figure are the overall channel, the discharge hydrographs (bottom), and the cumulative deposition or erosion at the treatment plant due to each size fraction. The behavior of the various size classes is clearly evident. No fine material (0.63 mm) is ever deposited. At the beginning of the "real" hydrograph, fine material begins to erode. The passage of the five-year flood accelerates the erosion. The STP sediments (.18 to 1.77 mm) accumulates rapidly prior to the "real" hydrograph, cease accumulating or erode slightly (1.77 mm) as the hydrograph passes, and erode away as the five-year flood passes. The inflow rate of .35 mm sand was sufficient to prevent complete scouring of the deposits by the five-year flood. The behavior of the channel bed at cross section 11, the first small impoundment, is illustrated in Figure 23.

It was concluded from these experiments that the model, coupled with flood frequency analysis, gave a reasonably powerful tool for analyzing the fate and resting time of deposits formed from the STP sediments. One condition which should be further investigated is the difficulty of separating the STP deposits when the STP sediments are identical to those in the flow or the channel bed or both. The Cuyahoga may be unique in the way the three size distributions vary. No general conclusions should be drawn about the fate of STP solids from these experiments. The Cuyahoga is fairly steep by stream standards. The movement pattern in a river of very flat slope comparable to that of the lower Mississippi with different sediment sizes should be investigated. Each STP and CSO will certainly be unique.

Particles with other specific gravities--

After determining that the model was capable of qualitative fate predictions for sand-like particles (recall that up to now all particles are quarts spheres of 2.65 specific gravity) experiments were conducted with sediments of varying specific gravities. The model was modified so that a specific gravity could be read in for each size class. The subroutines which calculated critical shear stress and fall velocities were modified accordingly. The reasoning behind the modification was to determine if the model could also be used to make qualitative judgements concerning the fate of heavy metal pollutants on other materials different from sands.

After the model was modified, small quantities of 0.63 mm particles with the specific gravities of lead and iron were introduced at the STP. The small size was used because pollutants are often adsorbed to fine particles. Flow conditions were identical to those used in earlier experiments. Note that under no circumstances do these experiments imply the presence of lead or iron in the outflow from the Akron STP. No actual data were available. Also, it should not be assumed that lead or iron would normally be found in their pure form. These elements were picked strictly because they represent a wide range of specific gravity.

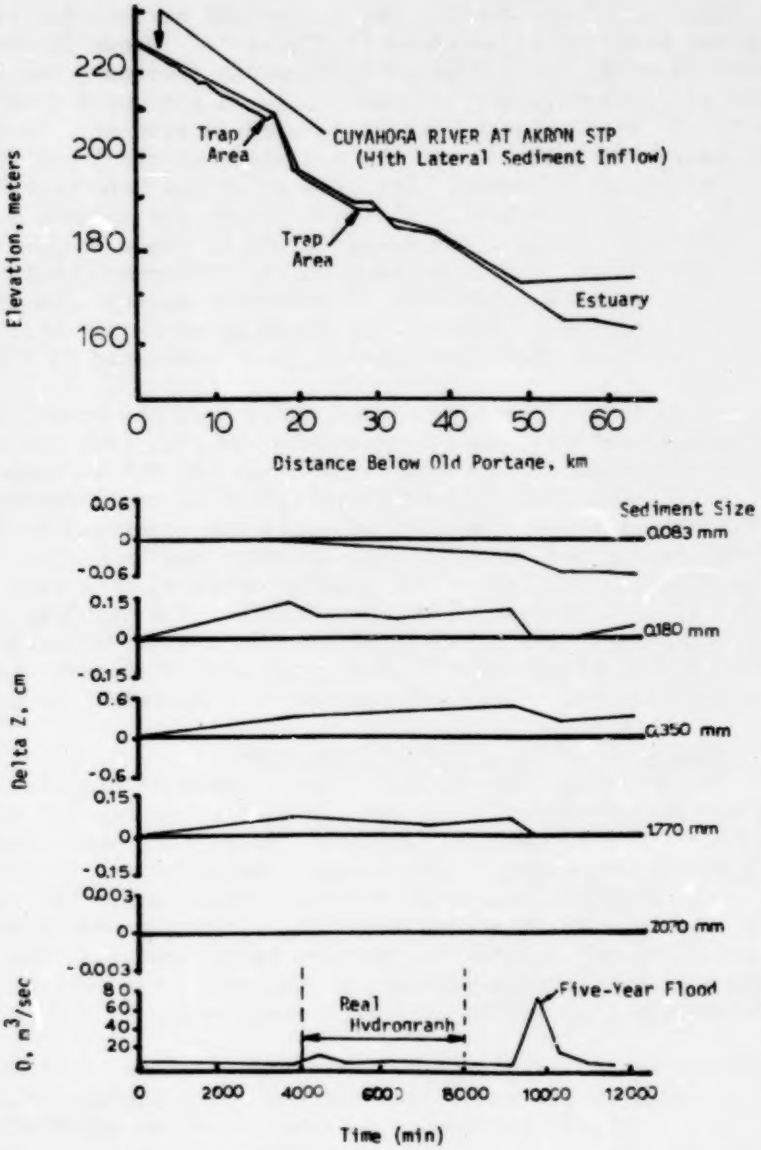

Figure 22. Deposition and Erosion at STP Outfall

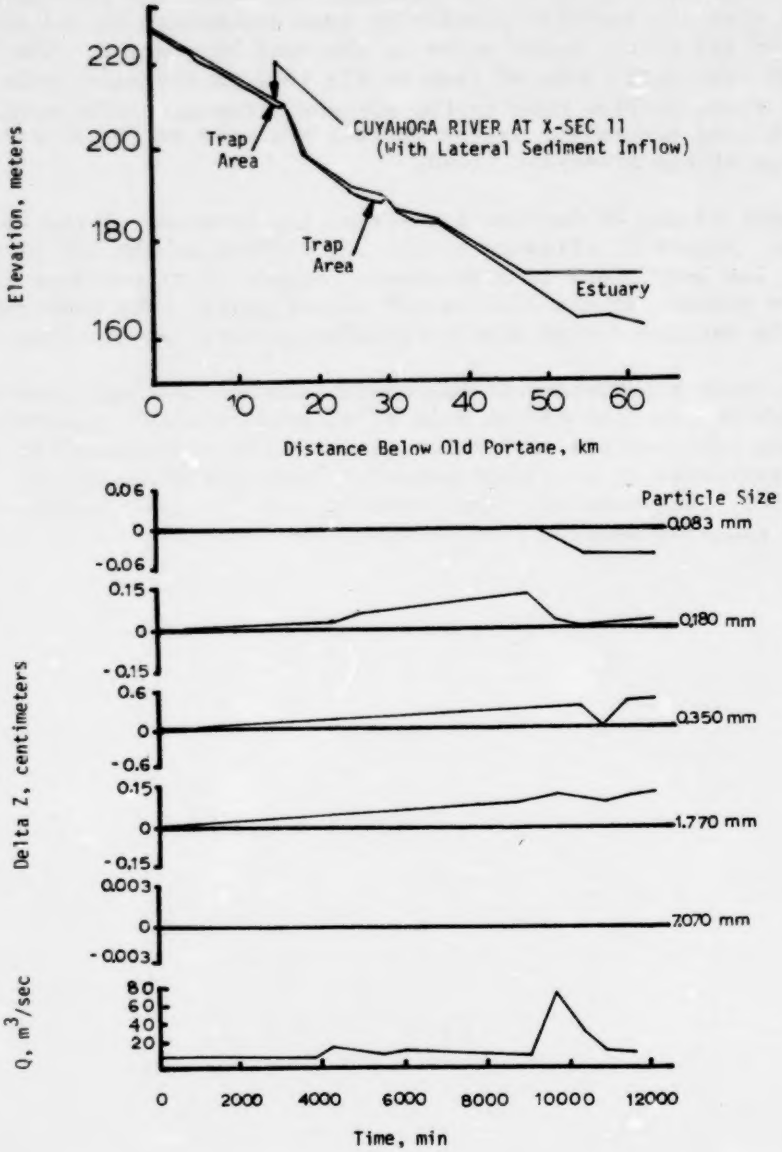

Figure 23. Deposition and Erosion Ten Miles Below Old Portage

Figures 24 through 26 illustrate the results of the experiments. Figure 24 illustrates the deposition areas for the two types of particles prior to the "real" hydrograph, after its passage, and after the five-year flood. The particles with the specific gravity of iron accumulate at the outfall and at the 16.1 km (10 mile) point prior to the real hydrograph. The "real" hydrograph transports most of them to the 16.1 km (10 mile) point and the five-year flood carries them to the estuary. The particles with the specific gravity of lead accumulate at the outfall and move to the 20 mile point with the passage of the five-year flood.

Figures 25 and 26 further illustrate the movement of the hypothetical particles. Figure 25 illustrates the aggradation at the STP as a function of time. The hydrograph is also shown. Figure 24 illustrates the aggradation and erosion at the 16.1 km (10 miles) point. The more ready movement of the particles with iron's specific gravity can be clearly seen.

From these experiments it was concluded that the model was capable of qualitative predictions of the fate of heavy particles. Quantitative predictions will require data which identify the size characteristics and specific gravities of pollutant material characteristics of the outfall (STP or CSO) being modeled. The following section describes methods of obtaining required data.

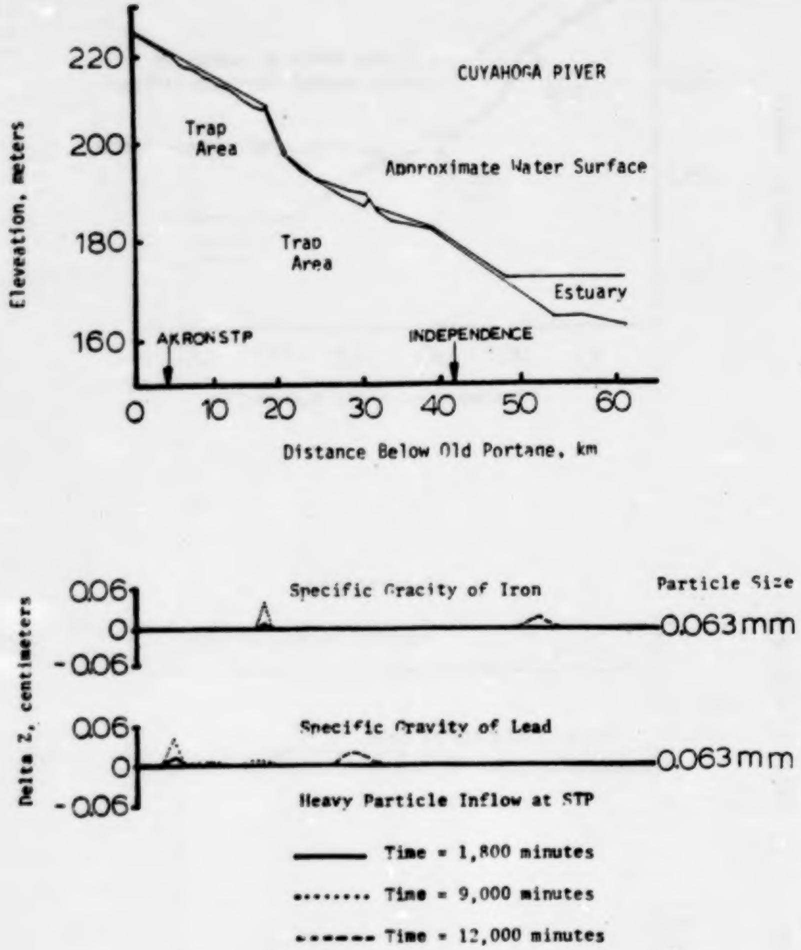

Figure 24, Deposition and Erosion of Heavy Particles

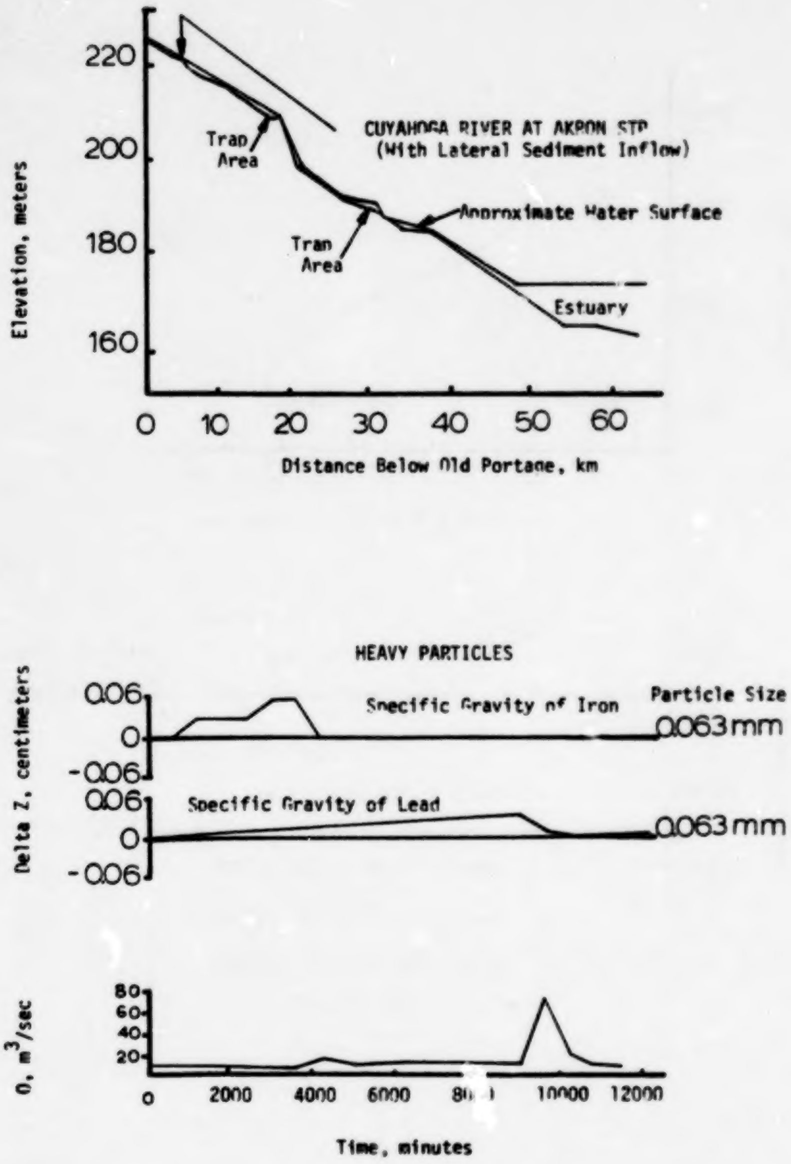

Figure 25. Deposition and Erosion of Heavy Particles at STP Outfall

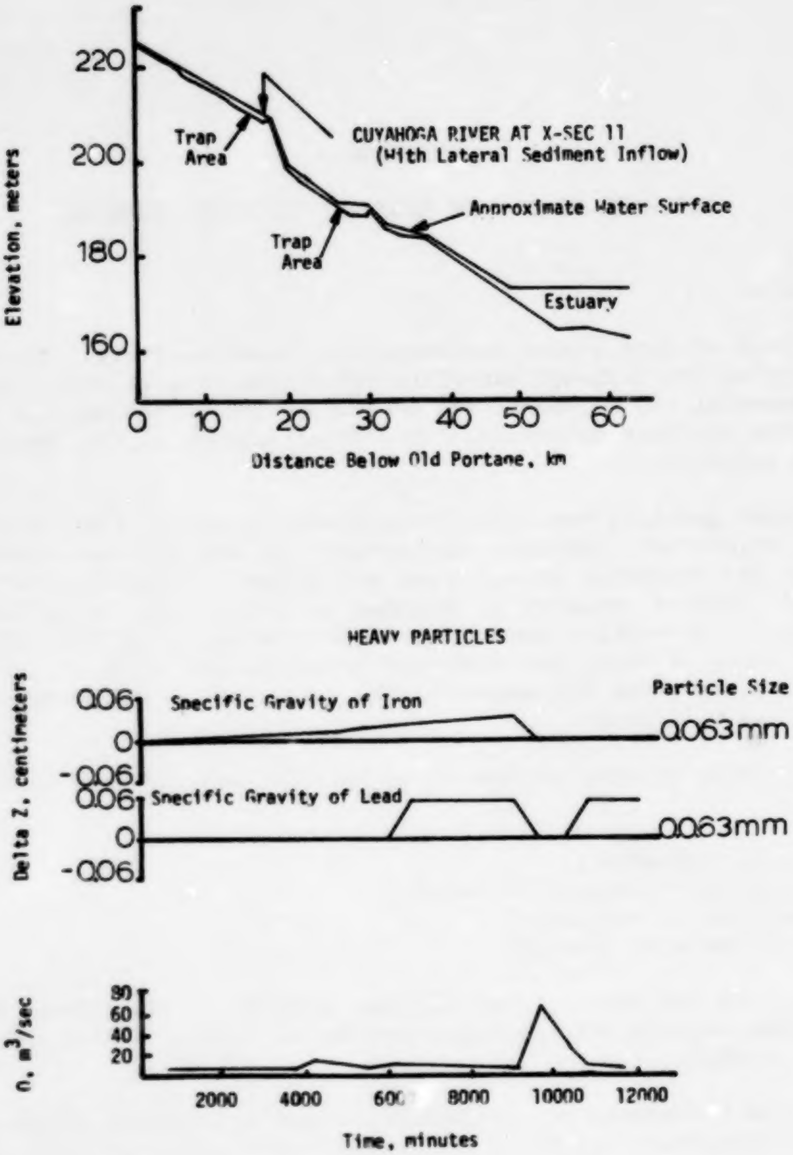

Figure 26. Deposition and Erosion of Heavy Particles Ten Miles Below Old Portage

SECTION 5

RELATED ASPECTS OF SEDIMENT TRANSPORT STUDIES

INTRODUCTION

The bulk of this report has dealt with three subjects. These are characterizing the sediment materials which come from combined sewer overflows, assessing their impact, and evaluating the technology for modeling the movement of these materials. This final section of the report deals with data problems.

Sediment modeling requires a significant amount of data on channel geometry, streamflow, sediment characteristics, and sediment movement. The techniques for obtaining geometry and streamflow information are widely understood. Stream geometry is obtained by standard surveying techniques or from maps. Streamflow data are routinely collected by the USGS and others by means of depth recorders and rating tables based on current meter measurements. Methods for measuring the rate of flow and movement of sediment are less well known.

The purpose of this section is to briefly summarize the techniques used to:

--sample sediments
--determine sediment flow rates
--characterize sediments
--trace sediment movement

The discussions are fairly brief and are designed to aid someone unfamiliar with sediment studies with an understanding of how to collect and use data for model studies.

Numerous references are available concerning sediment transport. The following discussions are based on several books in the writers' personal library and on publications of the United States Geological Survey. Probably the best general reference book on sediment transport is (54) from the American Society of Civil Engineers. Chapter III is devoted entirely to sampling techniques and their limitations. A second good book is (61) by Graf. Graf's Chapter 13 covers essentially the same materials as (5) but in greater detail. The book also has a somewhat more international flavor. Other good references are (61) and (63) by Simons and Senturk and

Bogardi. Bogardi gives one of the few descriptions of tracer techniques. The best detailed references on sediment analysis techniques are published by the USGS. References (64 and 65) on sampling techniques and analysis procedures are particularly useful.

SAMPLING SEDIMENTS

In general, two different but related sampling problems will be encountered in a model study. The first problem is to determine what type and quantities of material make up the channel bed and banks. The second problem is to determine what type and quantities of material are transported by the flow. Sampling the channel bed and bank material is fairly straightforward, as the composition is usually fairly stable with time. The quantity and type of material in the flow varies constantly both in time and space. In addition, a distinction is made between material actually suspended in the flow and that which moves mostly in contact with the bed. The second, is, thus, the more difficult problem. Both will be discussed here. Obtaining samples from the bed and flow will be discussed first. The process of analyzing the samples is largely the same regardless of the source and will be discussed last.

Bed and Bank Material Samples

The methods used to sample bed and bank material of streams are generally unsophisticated. The determining factor on the method used is somewhat a function of the size distribution of the particles.

The common shovel is an adequate tool to obtain most bank material samples in material up to 7 to 10 cm (3 or 4 inches) in diameter. Representative areas are picked and shovelfuls transferred to watertight sample bags. While these samples are not taken underwater, the watertightness is desirable to prevent the loss of the fine fractions. Note that a shovel is not a generally satisfactory tool for sampling underwater. Most of the fine material is washed away when the sample is withdrawn.

When bed material exceeds 7 to 10 cm (3 or 4 inches) sampling becomes more difficult. The USGS (66) describes an optional method for use in coarse sizes. All that is required is a photograph of the bed with a size scale such as a survey rod or ruler included. It is unlikely that such methods would be necessary in the average model study. The technology for modeling transport of coarse materials is limited. A bed consisting largely of 10 cm (4 inches) and up material would probably be treated as a rigid boundary.

The problem of sampling a streambed beneath flowing water has been studied in considerable detail. Several standard samples are available for this purpose. Guy and Norman (64) and ASCE (54) provide good descriptions. Reference (64) is considerably more detailed. Before describing the samplers, a short discussion from Guy and Norman concerning the standard codes used to identify approved sediment samples will be presented.

An array of standard samplers and methods have been developed by the Federal Inter-Agency Sedimentation Project (FIASP) of the Inter-Agnecy Committee on Water Resources, located first at Iowa City, Iowa and since 1948 at the St. Anthony Falls Hydraulic Laboratory in Minneapolis, Minnesota. Their reports cover almost all aspects of measurement and analysis of sediment movement in streams. A complete catalog of these reports is available in reference (11). The reader should refer to the FIASP reports for further background material and details on the standard samplers. Samplers carry the following coded designation:

US - United States standard sampler (after first use in designating a sampler in this chapter, it will usually no longer be included as part of the designation)

D - depth integrating

P - point integrating

H - hand held by rod or rope (for cable-and-reel suspension, the H is omitted)

BM - bed material

U - single stage

YEAR - year (last two digits) in which the sampler was developed.

The samplers described in this section are physically limited to those capable of collecting bed-material samples consisting of particles finer than about 30 or 40 mm in diameter. There may also be limitations with respect to some very fine sediments for some of the samplers. The collection and analysis of material larger than coarse gravel logically becomes more difficult and costly because other techniques are required to avoid handling heavy samples with larger and more expensive equipment. Because of the difficulty in measuring large sizes, little information regarding size distribution is available on streams having gravel, cobble, and boulder beds.

Bed material samplers, as first developed, may be divided into three types: the drag bucket, grab bucket, and vertical pipe. The drag-bucket sampler consists of a weighted section of cylinder with an open mouth and cutting edge. As the sampler is dragged along the bed, it collects a sample from the top layer of bed material. The grab-bucket sampler is identical in principle to the drag-bucket sampler. It consists of a section of a cylinder attached to a rod and is used in the collection of samples from shallow streams. Both samplers are operated by dragging upstream so that the mouth is exposed to the flow, which results in the loss of some fine material while in transit from the stream bed to the water surface. The vertical-pipe or core sampler consists of a piece of metal or plastic pipe that can be forced into the stream bed by hand.

The drag and grab-bucket sampiers are either too cumbersome to handle or do not obtain representative samples of the bed material. The vertical-pipe samples is satisfactory for use in shallow streams (54).

The Federal Inter-Agency Project has developed three types of instruments for sampling the bed material of streams where most of the material is finer than medium gravel. The smallest of the three, designated as the "US BMH-53" (see Figure 27), is designed to sample the bed of wadable streams. The collecting end of the sampler is a stainless steel thin-walled cylinder 2 inches in diameter and 8 inches long with a right-fitting brass piston. The piston creates a partial vacuum above the material being sampled and thereby compensates in a reverse direction for some of the frictional resistance required to push the sampler into the bed. This partial vacuum also retains the sample in the cylinder while the sampler is being removed from the bed.

The bed material of deeper streams or lakes can be sampled with the US BHM-60 (see Figure 28). This is a hand-line sampler about 22 inches (56 cm) long, made of cast aluminum, has tail vanes, and is available in weights of 30, 35, or 40 pounds (13.6, 15.9, or 18.2 kg). Because of its light weight, its use should be restricted to streams of moderate depths and velocities and whose bed material is also moderately firm and yet does not contain much gravel.

The sampler mechanism of the US BMH-60 consists of a scoop or bucket driven by a cross-curved constant torque, motor-type spring that rotates the bucket from front to back. The scoop, when activated by release of tension on the hanger rod, can penetrate into the bed about 1.7 inches (4.3 cm) and can hold approximately 175 cc of material. The scoop is aided in penetration of the bed by extra weight in the sampler nose (67).

The bucket closes when the sampler comes to rest on the streambed. A gasket on the closure plate prevents trapped material from contamination or being washed from the bucket.

Except for streams with extremely high velocities, the 100-pound cable-and-reel suspended BM-54 sampler (Figure 29) can be used for sampling bed material of streams and lakes of any reasonable depth. The body of the BM-54 is of cast steel. Its physical configuration is nearly identical with the cast aluminum BMH-60, 22 inches (56 cm) long and with tail vanes. Its operation is also similar to the BMH-60 in that it takes a sample when tension on the cable is released as the sampler touches the bed. The sampling mechanism externally looks similar to that of the BMH-60, but its operation is somewhat different.

In the event that core samples are needed in deep flowing water, a sampler has been developed and extensively used in studies of the Columbia River Estuary by Pyrch and Hubbell (68). This cable-suspended sampler collects a 4.76 cm (1-7/8 inch) diameter by 1.83 m (6 foot) long core by a combination of vibration and an axial force derived by cables from a 113 kg (250 pound) streamlined stabilizing weight.

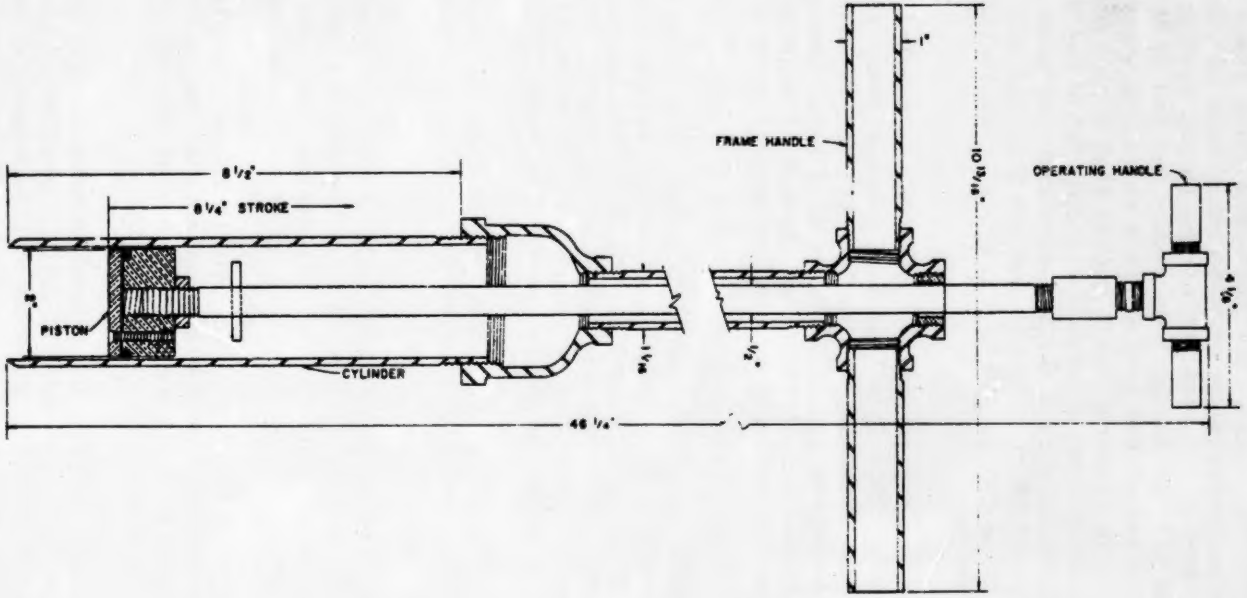
8 1/2"
8 1/4" STROKE
PISTON
2"
CYLINDER
1 1/16
1/2"
46 1/4"
FRAME HANDLE
1"
10 13/16"
OPERATING HANDLE
4 1/8"

Figure 27. US BMH-53--Bed Material Sampler (54)

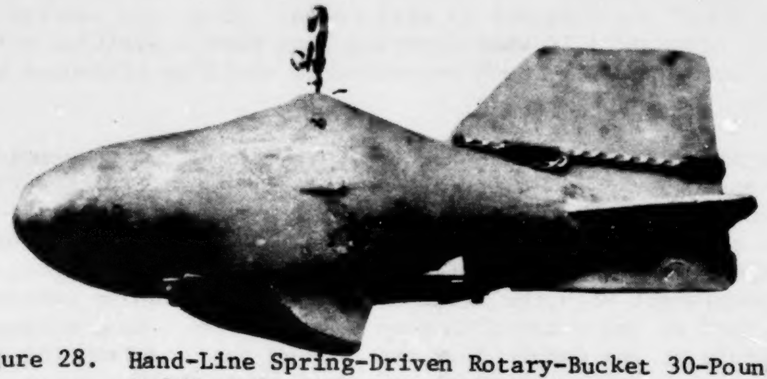

Figure 28. Hand-Line Spring-Driven Rotary-Bucket 30-Pound Bed-Material Sampler, US BMH-60 (11)

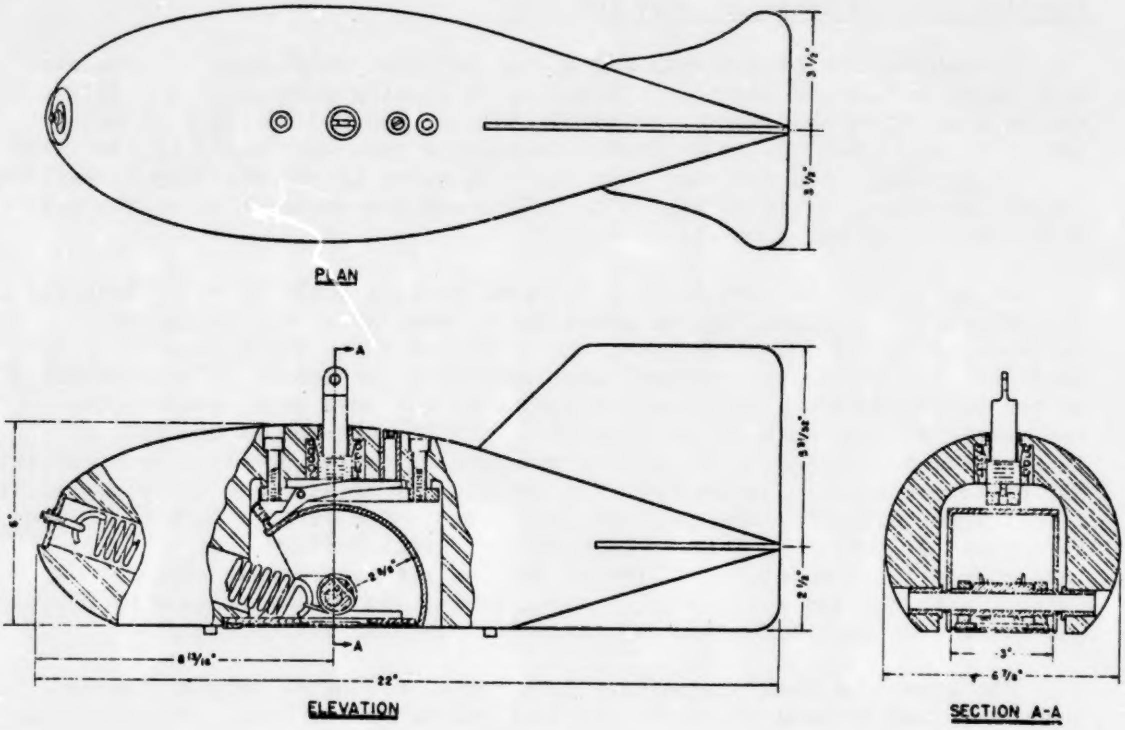
3 1/2"
3 1/2"
PLAN
A
A
6"
3 21/32"
2 5/8"
2 1/2"
8 13/16"
22"
ELEVATION
3"
6 7/8"
SECTION A-A

Figure 29. US BM-54--Bed Material Sampler (54)

In terms of collecting data for model studies, the three US standard samplers should be adequate in most cases. Long core samples would most likely be required only when studying long-term deposition rates in lakes or other impoundments. Such measurements would be connected with studies extending over several years.

A short discussion is in order concerning where to sample. Model studies such as discussed earlier in this report descretize the stream into fixed cross sections. Customarily, the sediment characteristics assigned to a single cross section are assumed to be representative of the stream halfway to the two adjoining sections. The objective of sampling is to produce values consistent with the model assumptions. Economic consideration usually dictate that as few samples as possible be taken. As a minimum, the writers prefer at least one sample from the channel and one from the overbank area at each cross section. If dollars allow, more samples should be taken in the channel to define the variations along the cross section. This is more important when the stream in question is always muddy and a visual determination of the nature of the bed is not possible.

Sampling Sediment Transported by the Flow

The objectives of any sampling of the material which flows by a sediment laden stream are twofold. First, it is usually desired to quantify the rate at which sediment is being discharged, usually in terms of weight per unit time. Second, itis usually desired to know what sizes of particles are being transported and what quantity. In order to successfully accomplish these objectives, it is necessary to understand how sediment materials are distributed in flowing water.

Depending on the size of each sediment particle, the stream transports the sediment by maintaining the particle in suspension with turbulent currents or by rolling or skipping the particles along the streambed (Saltation). The finer sediments move downstream at about the same velocity as the water, whereas, the coarsest sediments may move only occasionally and remain at rest much of the time (69). While material is transported in suspension, saltation, and rolling and sliding on the bed is also occurring. The different modes of transportation are closely related and it is difficult, if not impossible, to separate them completely. The borderline between contact load and saltation load is certainly not well defined. It is indeed hard to picture a particle rolling on the bed without at some time losing contact with the bed and executing short jumps. In a similar manner, the distinction between saltation and suspension is also not definite.

The term "bed load" is defined as material moving on or near the bed. The total load is made up of the bed load and suspended load. In addition, the total load is divided into "bed sediment load" and "wash load," which are defined as being, respectively, of particle sizes found in appreciable quantities and in very small quantities in the shifting portions of the bed. Obviously, both the bed sediment load and the wash load may move partially as bed load and partially as suspended load, although by definition, practically all the wash load is carried in suspension.

In terms of a model study, the term of most concern is "sediment discharge" which is defined as the quantity of sediment per unit time carried past any cross section of a stream. The term should be qualified. For example, one may refer to the bed load discharge, the bed sediment discharge, or the total sediment discharge. It will be noted that, as used herein, the term "load" denotes the material that is being transported, whereas the term "sediment discharge" denotes the rate of transport of the material (5). The model described in this report prints out the sediment discharge for each size class considered. The bed load discharge is calculated internally and not reported, although it could be if required. Our sampling techniques are, thus, directed toward measuring the suspended and bed load discharges or both, at once, if possible.

The distribution of the suspended-sediment sizes in the vertical direction may vary from stream to stream and from cross section to cross section within the same stream. Generally, the finer sediments are distributed uniformly throughout the vertical, and the coarser particles are concentrated near the streambed but with some coarse particles reaching the water surface at times (64). This behavior is illustrated in Figure 30. Figure 30 illustrates the difficulty of sampling the various sediment loads. Typical suspended sediment samples cannot reach the lower .09 to .12 m (0.3 to 0.4 foot) of flow.

The higher concentration and coarser sizes of sediment passing beneath the sampler nozzle, in suspension and on the bed, are difficult to measure. This unmeasured part may or may not be a sizable part of the total sediment (measured plus unmeasured) and is sometimes computed empirically for lack of suitable sampling devices.

At some stream cross sections, all the sediment sizes being transported may be thrown into a fairly uniform suspension throughout the entire vertical by natural or artificial turbulence. The measured part at these sites is representative of the entire vertical and represents total sediment discharge (64). When locating field measuring sections, such places are highly desirable. Locations where all the sediment is uniformly suspended offer the maximum measurement accuracy and require the fewest samples.

Two types of samplers will now be discussed. The first are suspended sediment samplers designed to measure from the water surface down to the "unsampled zone." The second are bed load samplers, designed to work at or in the channel bed.

Suspended Sediment Samplers--

Two types of suspended sediment samplers are generally used. The depth-integrating sampler collects and accumulates the sample as it is lowered to the bottom of the stream and raised back to the surface. The sampler must be moved at a uniform rate in a given direction but not necessarily at equal rates in both directions.

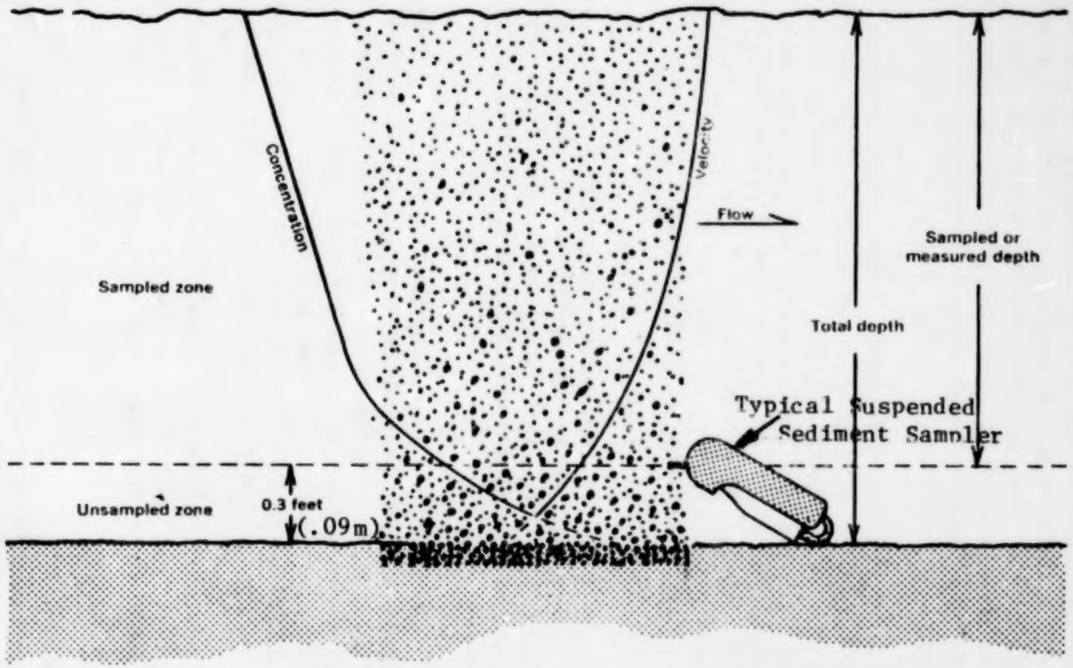
Concentration
Velocity
Flow
Sampled or measured depth
Total depth
Sampled zone
Typical Suspended Sediment Sampler
Unsampled zone
0.3 feet
(.09m)

Figure 30. Measured and Unmeasured Sampling Zones in a Stream Sampling Vertical with Respect to Velocity of Flow and Sediment Concentration (11).

The point integrating sampler, on the other hand, is designed to collect a time integrated sample at a single point in the flow. It can be operated to obtain a depth-integrating sample from deep or swift streams by holdling the valve open while integrating the stream depth in parts.

Where streams can be waded, or where a low bridge is accessible, a choice of two lightweight hand samplers can be used to obtain suspended-sediment samples. The smallest of the two is designated "DH-48" (Figure 31). It consists of a streamlined aluminum casting 13 inches (33 cm) long which partly encloses the sample container. The container is usally a round pint glass milk bottle. A standard stream-gauging wading rod, or other suitable handle, is threaded into the top of the sampler body for suspending the sampler. The instrument can sample to within 3-1/2 inches (9 cm) of the streambed.

The other lightweight sampler, designated "DH-59," (Figure 32) was designed to be suspended by a hand-held rope in streams too deep to be waded. It too only partly encloses the sample container. Because of its light weight, it is limited in use to streams with velocities less than about 5 fps.

These two lightweight hand samplers are the most commonly used for sediment sampling during normal flow in small and perhaps intermediate sized streams. Because they are small, light, durable, and adapatable, they are preferred by hired observers and fieldmen on rountine or on reconnaissance measurement trips. At most locations, a heavier sampler will be needed only for high flow periods.

When streams cannot be waded, but are less than 15 to 18 feet deep, depth-integrating samplers designated "D-49" can be used to obtain suspended-sediment samples. The D-49 resembles a small bronze submarine. It weights approximately 62 pounds (28 kg). The design is compatible with cable and reel suspensions used with current meters.

Point-integrating samplers are more versatile and, consequently, more complex than the simpler depth-integrating types. They can be used to collect a sample that represents the mean sediment concentration at any selected point beneath the surface of a stream except within a few inches of the bed, and also to sample continuously over a range in depth. They are used for depth-integration in streams too deep (or too swift) to sample in a round-trip integration. In depth integration, sampling can start at any depth and continue in either an upward or downward direction for a maximum vertical distance of about 30 feet.

The US P-46 consists of a 100-pound (46 kg) streamlined cast bronze shell, an inner recess to hold a round pint milk bottle, a pressure equalizing chamber and a tapered three position rotary valve operated by solenoid which controls the sample intake and air exhaust passages.

The 105 pound (48 kg) US P-61 (Figure 33) is similar to the P-46, but is simpler and somewhat less expensive. It can be used for depth

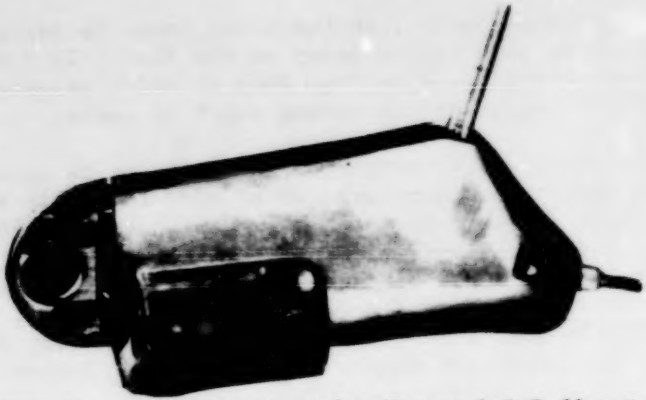

Figure 31. Depth-Integrating Suspended-Sediment Wading-Type Hand Sampler, US DH-48

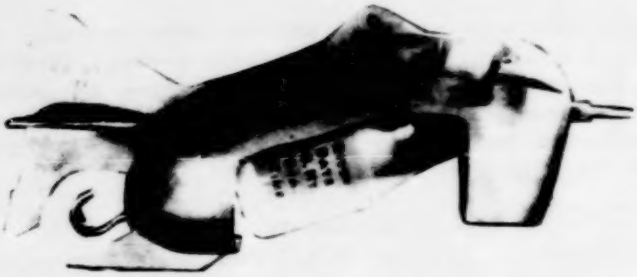

Figure 32. Depth-Integrating Suspended-Sediment Hand Type Sampler, US DH-59

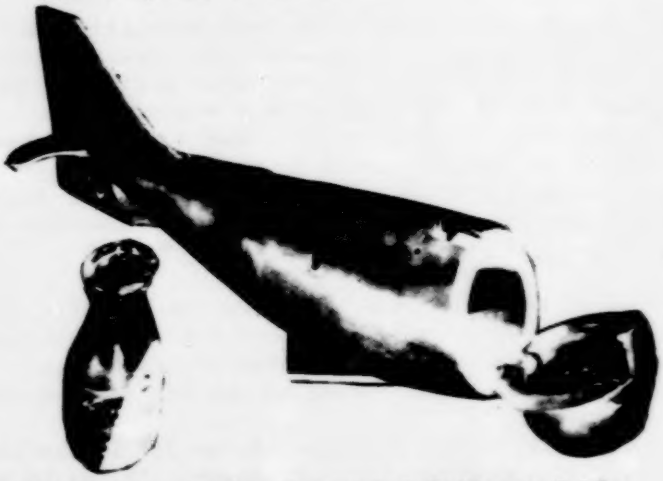

Figure 33. Depth-Integrating Suspended-Sediment Cable and Reel Sampler, US D-49

integration as well as for point integration to stream depths of at least 180 feet (55 m).

The US P-63, a 200 pound (91 kg) electrically operated suspended sediment sampler, is better adapted to very great depths and high velocities. The P-63 differs from the the P-61 mainly in size, weight, and in the capacity of the sample container that can be used. It has the capacity for a quart-sized round milk bottle. An adapter is furnished so that a round pint-sized milk bottle can be used. The maximum sampling depth is about 180 feet (55 m) with a point sample container and 120 feet (37 m) with a quart container.

The 300 pound (136 kg) US P-50 is designed for use in extremely deep streams and high velocities. Its operating characteristics are similar to the P-63 (48). All the point samples are designed for suspension with a steel cable having an insulated inner conductor core. By pressing a switch located at the operators station, an electric current opens a valve to allow the sample in.

Because of the complex nature of point integrating samples, the reader may find it necessary to seek additional information from USGS or FIASP reports.

Occasionally the modeler will need to collect data on sediment inflow from small tirbutaries. Such tributaries may be difficult to reach or flow only intermittently. The single-state sampler, US U-59, was tested by the FIASP to meet the needs for an instrument that would obtain some sediment data on small fast-rising streams where it is impractical to use a conventional depth-integrating sampler.

The US U-59 sampler consists of a pint milk bottle or other sampler container, a 3/16 inch inside diameter copper tube intake. Each tube is bent to an appropriate shape and inserted through a stopper which fits tightly into the top of the container. There are two general types of this sampler, one with a vertical intake and the other with a horizontal intake. The U-59 is illustrated in Figure 34.

When the stream surface rises to the elevation of the intake nozzle, the water-sediment mixture enters; and as the water surface continues to rise in the stream, it also rises in the intake. When the water-surface, elevation W reaches C, flow starts over the weir of the siphon, primes the siphon, and begins to fill the sample bottle. The sampling operation just described is somewhat idealistic because in reality the operation is affected by the flow velocity and turbulence which alters the effective pressure at the nozzle entrance.

The U-59 has many limitations with respect to good sampling objectives. It must be considered a type of point sampler because it samples a single point in the stream at whatever stage the intake nozzle is positioned before a flow event occurs. Its primary purpose is to collect a sample automatically, and it is used at stations on flashy streams or other locations where extreme

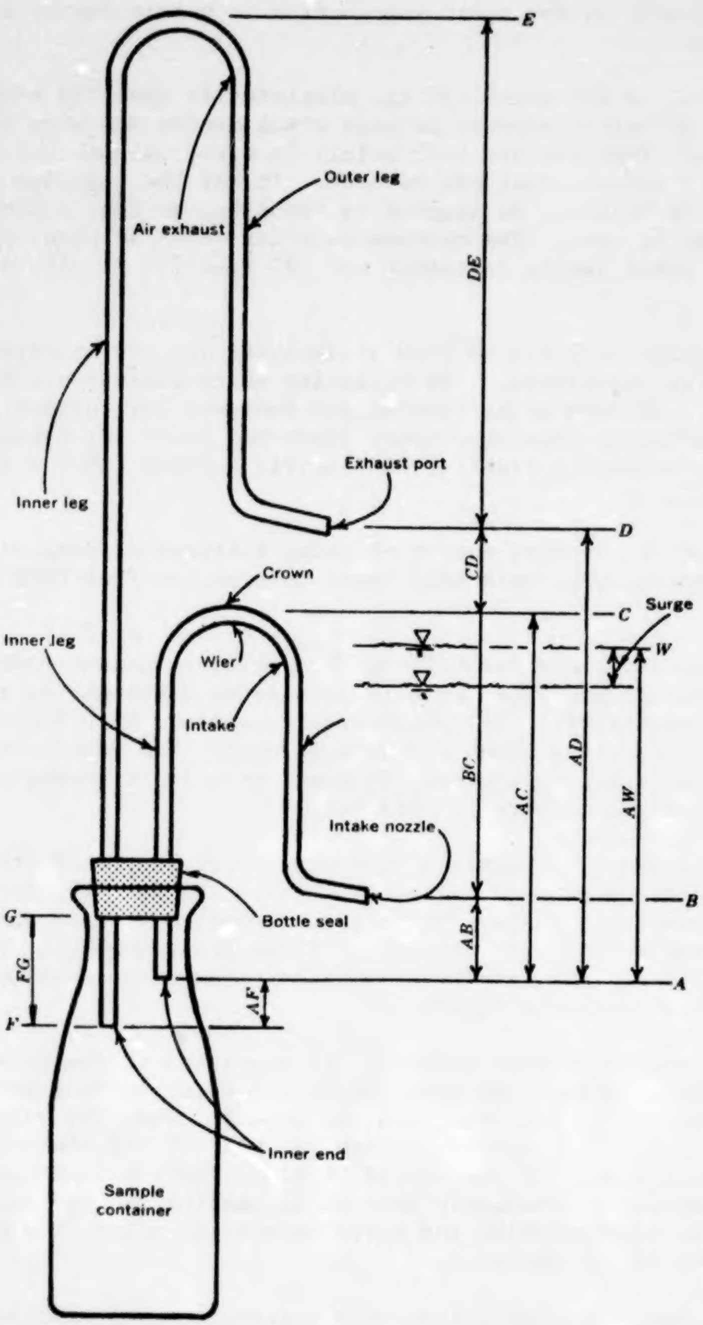
E
Outer leg
Air exhaust
DE
Inner leg
Exhaust port
D
CD
Crown
C
Surge
Inner leg
Wier
W
Intake
BC
AC
AD
AW
Intake nozzle
B
Bottle seal
AB
G
FG
AF
A
F
Inner end
Sample container

Figure 34. Components and Dimensions of the Basic Single-Stage Suspended-Sediment Sampler, US U-59, (64).

difficulty is encountered in trying to reach a station to collect samples at appropriate times by the normal procedure with standard equipment.

A number of manufacturers have developed automatic point samplers. In general, these use timed pumps which extract the sediment water mixture from a point in the flow and transfer it to one of several bottles in a rotating rack. These can be quite useful when continuous records fora model are required. Supplemental measurements must still be made with samplers discussed earlier to aid in extrapolating the point data to an entire cross section.

Bedload Samplers--

Up to this point we have discussed means for determining the quantities of sediment in the upper portion of the depth of a stream (Figure 30). We will now look at means for determining the quantity of sediment which flows near the bed.

At this time the reader may wish to note the difference between bedload and unmeasured load. Bedload is the sediment that moves in the stream at velocities less than the surrounding flow by sliding, rolling, or bouncing on or very near the streambed. The size particles moving as bedload is identical with samples of bed material in the movable part of the streambed. Unmeasured load is that sediment which is not measured with the suspended-sediment samplers and consists of bedload particles and particles in suspension in the flow below the sampling zone of the suspended-sediment samplers (Figure 30).

Bedload is difficult to measure for several reasons. Any mechanical device placed in the vicinity of the bed will disturb the flow and hence the rate of bedload movement. Another reasonwhy bedload is difficult to measure is that the sediment movement and the velocity of water close to the bed vary considerably with respect to both space and time; and, therefore, if a good sample could be obtained at a given point, it may not be representative of the entire cross section for a reasonable interval of time (48).

The bedload discharge, therefore, cannot be determined in the same manner as suspended-sediment loads through computation by use of suspended concentration and water discharge data. Thus, a bedload sampler must be able to effectively trap all particles moving along the bed when and if they pass over an area of the undisturbed bed in a specified period of time.

Many agencies all over the world have developed their own bed load measuring devices. However, these devices are, at least in principle, quite similar. They can be distinguished as (1) devices called bed load samplers or catchers, (2) direct observation of the movement of bed forms, and (3) sonic samplers. Rather than direct measurement, bed load movement can be computed by one or more of several different formulas. CSU sediment model already incorporates one of these, the Meyer-Peter and Mueller method. In addition, periodic quantity surveys of sediment deposits may give a rasonable estimate of the bed load rate.

Similar to other hydrometric devices, the bed load samplers must be calibrated. Calibration of a sampler consists of determining its efficiency coefficient, that is, the ratio of bed load indicated by the sampler to the true bed load. Efficiencies of bed load samplers have been determined in laboratory flumes with fixed and movable beds.

The bed load samplers may be generally classified as the following types: box- and basket-type samplers, pan-type samplers, and pit-type samplers. The box-basket samplers consist of a pervious container where bed load accumulates, of a supporting frame and cables to make the samples portable, and of a vane to give the sampler the appropriate direction. The pan-type samplers consist of a pan with a bottom and two side-walls. Within this pan there may or may not be a baffle system to retard the water-sediment mixture and, thus, trap the sediment. The pit-type samplers consist of a depression (pit) installed in the channel bottom to catch and accumulate the bed load which is removed by a mechanical device to obtain a continuous record. Among the three types of samplers, the box- and basket-type samplers are most common (54).

The current state-of-the-art of bedload samplers is so poor that the writers recommend they be avoided. At the time of this writing, the procedures for calculating the bedload discharge based on the suspended load discharge are just as accurate as sampling. If sampling is necessary, up-to-date information on methods can be obtained by contacting the US Geological Survey's Research Laboratory, St. Anthony Falls, Minneapolis, Minnesota. and the Sediment Research Center in Denver, Colorado.

DETERMINING SEDIMENT FLOW RATES

It is one problem to obtain sediment samples from the flow field and another to determine the discharge of sediment from these samples. Using the suspended-load measuring devices discussed previously, one can obtain suspended-load samples at any location and time. However, these samples may or may not yeild concentrations truly representative of the mean suspended-sediment concentration for the entire cross section. Ideally, the best procedure for sampling any stream for sediment concentration, as related to discharge, would be to collect the entire flow of the stream for a given period of time. For practical reasons such a method cannot be employed. Consequently, some system for selecting limited numbers of samples must be used (54).

The most common methods that have been used to locate the transverse positions of sampling verticals are:

--single vertical at midstream,
--single vertical at thalweg or point of greatest depth,
--verticals at 1/4, 1/2, and 3/4 width,
--four or more verticals at midpoints of equal width sections, or equal transit rate (ETR) at all verticals, and
--verticals at centroids of equal discharge increments (EDI) across the stream.

Obviously, the simplest practice is the selection of a single sampling vertical at midstream or at thalweg. However, a single vertical should only be used in a very small stream or in certain types of routine sampling when there is adequate mixing and accuracy is not important.

Selection of sampling at the 1/4, 1/2, and 3/4 width of a stream cross section is convenient and practical. This method provides more information concerning the distribution and discharge of sediment than the single-vertical method.

The ETR and the EDI methods are generally adopted in important investigations. These are sufficiently complex that a discussion cannot be included here. Reference (54) should be consulted for procedures and formulas. In general, these require a sound knowledge of stream gauging practice. In terms of model studies, the ETR and EDI methods would probably only be used at key points such as the downstream end of the model reach. Such detailed measurements would be important to obtain accurate data for model calibration.

It is worth pointing out at this time that a knowledge of the water discharge is vital to determining the sediment discharge. The general procedure is to analyze a sediment sample for concentration of sediment by weight and compute concentration. This is true whether one sample or several are collected. In the simplest case, the water discharge may be read from a rating curve at a gauging station. In the worst case, current meter measurements must be made at the same time the samples are collected.

As noted earlier, the sediment sampling equipment is limited mostly to the collection of suspended-sediment and bed-material samples from streams. The suspended-sediment sampler can sample to only within a few tenths of a foot of the streambed. The sampled part is referred to as carrying the measured load and the unsampled zone as carrying the unmeasured load (Figure 30). The unmeasured load contains both unmeasured and suspended-sediment load and the unmeasured bedload. (Bedload is that material transported in a stream by sliding, rolling, and bouncing along the bed and very close to it, that is, within a few grain diameters.) Total load, then, is the sum of the measured and unmeasured load.

There are some streams with sections so turbulent that nearly all sediment particles moving through the reach are in suspension. For instance, the Cuyahoga River reach used for the present study had several reaches where this was true. Sampling and suspended sediment in such sections with a standard suspended-sediment sampler then very nearly represents the total load.

Turbulence flumes or special weirs can be used to bring the total load into suspension. Total load can usually be rather accurately sampled where the streambed consists of an erosion resisting material such as bedrock or a very cohesive clay. In such situations, the majority, if not all, the sediment being discharged is in suspension or the bed would contain a deposit of sand. Most total load sampling is accomplished at the crest of small weirs, dams, culvert outlets, or other places where all sediment must be in suspension.

Where such conditions or structures are not present, the unmeasured load must be computed by various formulas. The reader concerned in detail should consult reference (11).

CHARACTERIZING SEDIMENTS

It is beyond the scope of this report to present complete laboratory procedures for analyzing sediment samples. Instead, the intent is to point out those characteristics important to modeling and provide a brief description of how they are determined. The single best reference on sediment laboratory procedures is (49) by Guy and Norman. The serious reader should obtain a copy from the USGS to obtain full details on laboratory procedures. Chapter II of (54) also contains much useful information. The discussion here is edited from these two references.

Definitions

Before proceeding directly to analysis, it is worthwhile to review the assumption within the model. At the same time, some standard analysis terminology will be introduced.

The sediment model evaluated in this report assumes that all sediments are noncohesive, spherical particles, with fixed specific gravities. The spherical particles are divided into fixed sizes. That is, the 0.63 mm size class is all assumed to be exactly 0.063 mm in diameter. Obviously, real sediment particles are neither spherical or fixed in specific gravity. The analysis problem then is to take a real sediment sample and analyze it in such a way that information fixed to the model is consistent with the assumptions. In order to accomplish this, the following standard terminology is introduced (65):

--The nominal diameter of a particle is the diameter of a sphere that has the same volume as the particle.

--The sieve diameter of a particle is the diameter of a sphere equal to the length of the side of a square sieve opening through which the given particle will just pass.

--The standard fall velocity of a particle is the average rate of fall that the particle would attain if falling alone in quiescent, distilled water of infinite extent and at a temperature of 24°C.

--The standard fall diameter, or simply fall diameter, of a particle is the diameter of a sphere that has a specific gravity of 2.65 and has the same standard fall velocity as the particle.

--The sedimentation diameter of a particle is the diameter of a sphere that has the same specific gravity and terminal uniform velocity as the given particle in the same sedimentation fluid.

--The standard sedimentation diameter of a particle is the diameter of a sphere that has the same specific gravity and has the same standard fall velocity as the given particle.

--Size distribution, or simply distribution, when applied in relation to any of the size concepts, refers to distribution of material by percentages or proportions by weight.

--Fall velocity and settling velocity are genrally terms which may apply to any rate of fall or settling as distinguished from standard fall velocity.

By examining the above terminology, it can be seen that the model used in the study could be operated in two quite different ways. First, all the particle sizes could be assigned a specific gravity of 2.65. Sediment samples would then have to be analyzed in such a way that the percent of material having a certain standard full diameter could be determined. Using this method, it would not matter how big a particle was or what is actual specific gravity was but only how rapidly it would settle out of suspension. Hydraulic analysis techniques which sort the sample by immersion in fluid are required. The second method is to assign each of the size fractions in the model a particular specific gravity. Samples must then be sorted by physical size (nominal diameter) and then by weight within a size fraction. In terms of fate and effect studies, the latter has an advantage when it is known that particular pollutants (say heavy metals) attach to specific size fractions.

Sample Analysis

In the earlier discussion of sampling techniques, two different types of samples were described. The first was a single material sample. These are taken to characterize the bed and bank sediments. The second was a suspended sediment sample. These are taken both to characterize the sediments being transported and to determine the transport rate.

Reference (65) provides two flow charts which describe the sequence of analysis for the two types of samples. These two flow charts are reproduced in Figures 35 and 36. Analysis of a bed or bank material sample is somewhat simpler and will be discussed first. Each box in the flow charts represents an anlaysis procedure. Boxes divided by horizontal lines indicate that more than one procedure may be used to accomplish the same result.

Bed Material Sample Analysis--

Note that the analysis of a bed material sample is generally divided into three parts. There is a part dealing with coarse, medium, and fine particles. Coarse, in this case, means particles greater than approximately 2 mm and fine means particles smaller than 0.063 mm. The reason for the three parts is that various methods of analysis are limited in the range of particle sizes they can accommodate.

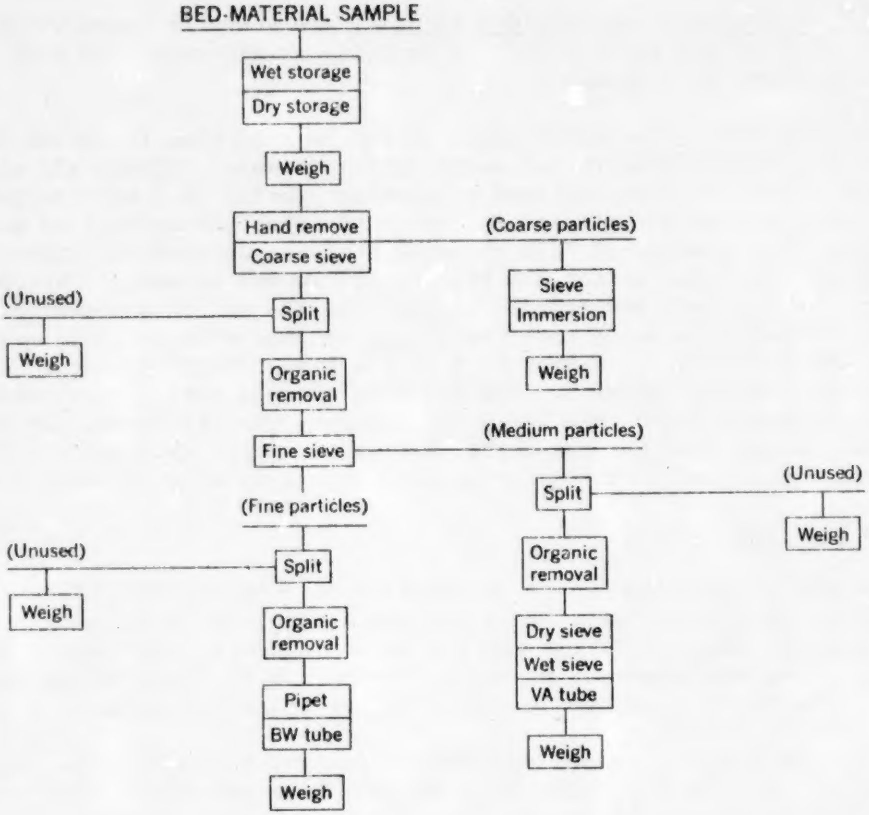
BED-MATERIAL SAMPLE
Wet storage
Dry storage
Weigh
Hand remove
Coarse sieve
(Coarse particles)
Sieve
Immersion
Weigh
(Unused)
Split
Weigh
Organic removal
Fine sieve
(Medium particles)
Split
(Unused)
Weigh
(Fine particles)
(Unused)
Split
Weigh
Organic removal
Organic removal
Dry sieve
Wet sieve
VA tube
Weigh
Pipet
BW tube
Weigh

Figure 35. Flow Chart for Bed and Bank Material Analysis

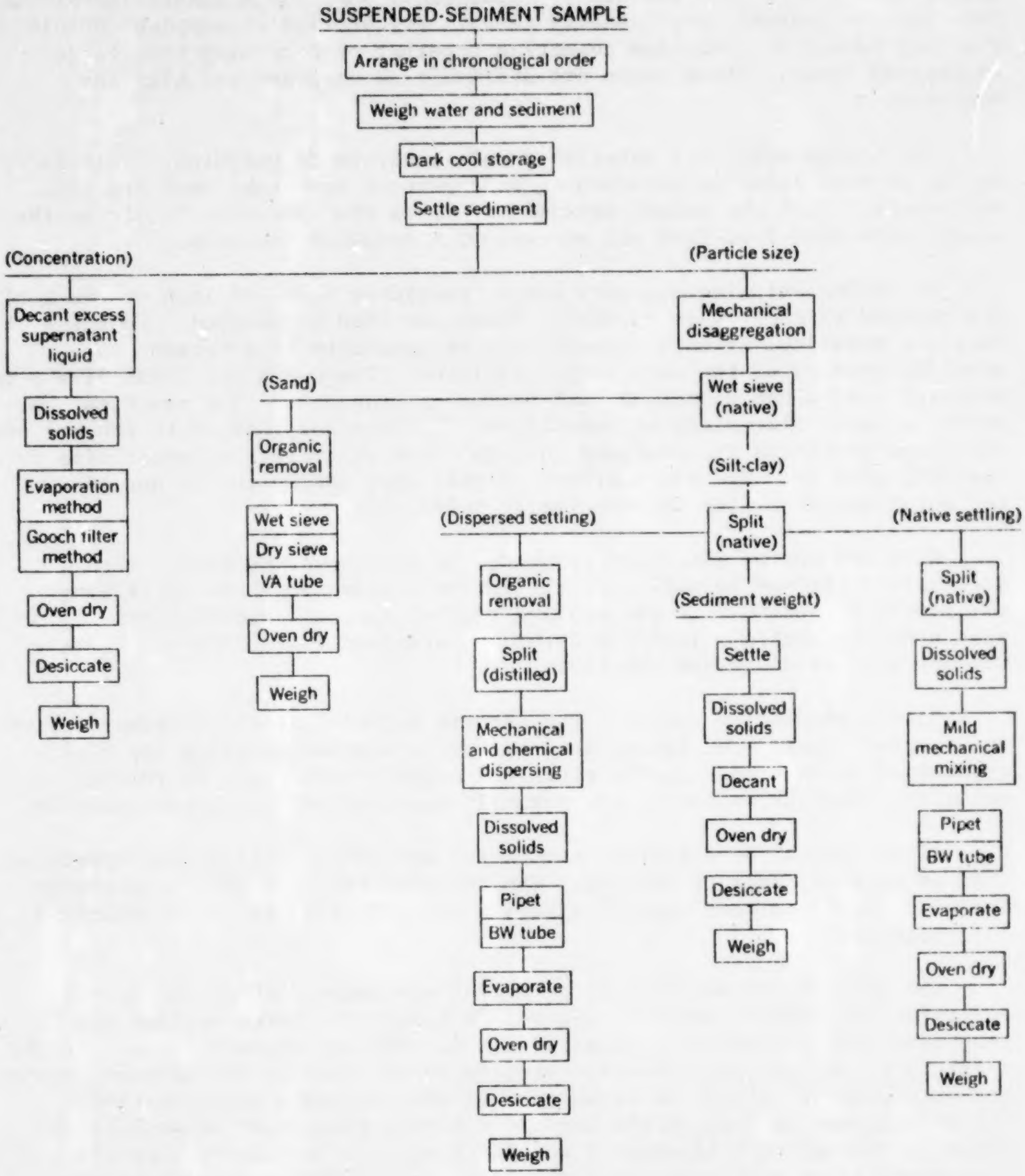
SUSPENDED-SEDIMENT SAMPLE
Arrange in chronological order
Weigh water and sediment
Dark cool storage
Settle sediment
(Concentration)
(Particle size)
Decant excess supernatant liquid
Dissolved solids
Evaporation method
Gooch filter method
Oven dry
Desiccate
Weigh
Mechanical disaggregation
(Sand)
Wet sieve (native)
Organic removal
Wet sieve
Dry sieve
VA tube
Oven dry
Weigh
(Silt-clay)
(Dispersed settling)
Split (native)
(Native settling)
Organic removal
Split (distilled)
Mechanical and chemical dispersing
Dissolved solids
Pipet
BW tube
Evaporate
Oven dry
Desiccate
Weigh
(Sediment weight)
Settle
Dissolved solids
Decant
Oven dry
Desiccate
Weigh
Split (native)
Dissolved solids
Mild mechanical mixing
Pipet
BW tube
Evaporate
Oven dry
Desiccate
Weigh

Figure 36. Flow Chart for Analysis of Suspended Sediment Samples (65)

The first step involved in analysis is storage. Samples may be stored either wet or dry. Wet storage is recommended when large quantities of fine material are present, particularly clays. Dry storage of samples containing clay may result in particles cementing together or hardening into large aggregated lumps. These lumps are difficult to disperse and bias the analysis.

The second step in a material sample analysis is weighing. This information is used later in determining what percent by weight each fraction represents. With the weight determined, it is then possible to divide the sample into size fractions and proceed with detailed analysis.

Following weighing the very coarse particles (say 1/2 inch or greater) are removed by sieving or by hand. These can then be weighed. In terms of data for modeling, it will probably not be necessary to determine the specific gravity of the very large particles. These are the least likely to move and are seldom connected with pollutant transport. For practical purposes, a large size class is established in the model (say 20 to 100 mm) and all large particles are assigned to this class regardless of exact size or specific gravity. The exact effect of this type assumption is not known but doing anything else is practically infeasible.

With the coarse particles removed, the sample may be larger than necessary. It may be split and the unused portion weighed. Splitting the sample to obtain a representative smaller amount is particularly important when using hydraulic methods to determine standard full diameter. These methods will be discussed shortly.

Before proceeding further, the organic material should be removed from the sample. Small root hairs, leaf matter, and other organics may bias results of later tests. Large pieces of organic matter may be removed manually. Smaller particles are normally oxidized with hydrogen peroxide.

After removal of organics, the medium and fine fractions are separated. This is normally done by sieving. The two fractions can then be analyzed individually for either nominal size and specific gravity or for standard full diameter.

The analysis of medium size particles may begin with an additional splitting and organic material removal if required. Three options are then available for particle classification. Two are sieve methods. If the model is to be used for fate-type studies as was done in the present report. the particles are sieved to separate them into suitable size fractions. The sieving may be done by shaking dry material through or by washing the material through with streams of water. The latter method is generally faster and gives more consistent results. It is often assumed that sieve diameter and nominal diameter are equal. The writers feel this is an adequate assumption for modeling purposes. The third method of analysis for medium particles is the visual accumulation tube (VA). A uniformly mixed sample is released from the top of a long water column. The particles sort themselves hydraulically and accumulate at the bottom of the column at times proportional to their standard full diameter (assuming the temperature of the column is appropriate). An optical tracking device on the tube coupled to a chart recorder allows direct determination of percent finer versus full diameter curves. Use of the VA tube method requires that the model be run using uniform specific gravities for all size classes. The remaining step in the analysis of medium particles is weighing. In the case of sieve analysis, the portions on each sieve are weighed and the percentage of the total sample determined. In the case of the VA tube, the entire sample is weighed as the percent-finer graph used to determine what percent is what size.

The analysis of the fine particles is, in ways, quite similar to the analysis of the medium particles. The sample is split, if required, the the unused portion weighed, and the organic material removed.

Two methods are available for the analysis of the fine particles. These are the pipet and bottom withdrawal (BW) tube methods. In the pipet method, a graduated cylinder filled with distilled water and a suitable volume of sediment is agitated until the sediment is fully mixed. A special hydrometer is inserted and the specific gravity of the mixture as a function of time recorded. From this information, a standard full diameter versus percent finer curve can be calculated. The bottom withdrawal tube method is similar in some ways. A full column filled with a uniform mixture of sediment and water are used. At time zero, the column is fully mixed. Samples are withdrawn from the bottom at specified intervals, dried, and weighed. A calculation procedure yields standard full velocity versus percent finer data.

In terms of model studies, the techniques most likely to be used are sieve analysis and the VA tube. In order to determine, for example, the fate of 0.063 mm particles with specific gravities of 4.0, it would first be necessary to sieve the sample to determine what percent of the total was 0.063 mm. Next, all the 0.063 mm particles or a representative sample would be VA tube analyzed to see what percent had full velocities equivalent to particles with specific gravities of 4.0.

Suspended Material Sample Analysis--

The various procedures for analyzing a suspended sediment sample are illustrated in Figure 36. There are two major differences in the analysis of a suspended material sample. First, one objective is to determine the concentration of material by weight suspended in the flow. Second, there are usually no particles larger than sand found in suspension. Thus, much of the analysis concentrates on the fine material fraction (less than 0.063 mm). The determination of concentration will be discussed first, followed by a discussion of the particle size diameter analysis.

If the concentration of a suspended material sample is to be determined, it will be necessary to store both the particulate material and the water from the samples. The first step in analysis is to determine the weight of the sediment-water mixture. If long-term storage is required a cool, dry place is recommended to discourage flocculation of the clays and other adverse chemical reactions.

The determination of concentration is straighforward. Generally, the sediment is allowed to settle and the excess liquid decanted. The liquid may be analyzed for dissolved solids. The weight of sediment may be determined by either filtration or simple evaporation plus weighing. The concentration is determined from the formula:

$$C, mg/\ell = f \frac{\text{weight of sediment} \times 1{,}000{,}000}{\text{weight of water sediment mixture}}$$

where f is a factor ranging from 1.0 to 1.34 depending on the weight ratio. The factor accounts for the fact that part of the water sediment mixture is occupied by the sediment and is used because weight is easier to determine accurately than volume.

The particle size analysis for the suspended material begins with disaggregation if required. This assumes that concentration was determined and that the drying process has bonded many of the particles together due to the presence of clays and silts. Disaggregation reseparates the particles if required.

The remainder of the analysis of suspended sediment samples does not differ a great deal from the analysis of bed material samples. The sand fraction (greater than 0.063 mm) may be wet or dry sieved or a VA tube analysis performed. The fine material may be simply dried and weighed or it may be analyzed in detail using the BW tube or pipet technique.

The pipet technique has not been discussed yet. It is similar to the BW tube method in that analysis starts at time zero with a uniformly mixed suspension of fine particles. A pipet is used to withdraw samples from a fixed level in the mixture at predetermined times. The concentration provides information on percent finer versus full diameter.

Given the current state of modeling, it is likely that simply weighing the fine fraction to determine its percentage of the total would be adequate. Sieve methods combined with the VA tube as described for the bed material sample would meet the remainder of analysis requirements.

TRACING SEDIMENT MOVEMENT

The difficulty involved in tracing the movement of a sediment particle is obvious. Movement is governed by particle shape, size, specific gravity, the position relative to other particles, the temperature and properties of the flow and many more. It is thus not surprising that tracer methods are not widely used.

The purpose of this section is to provide a very brief look at the types of studies which have been attempted. The coverage is not exhaustive but should give the reader an idea of the problems involved and the type of infomration attainable.

Only two readily available references discuss tracer techniques in any detail. These are references (61) and (63) by Graf and Bogardi, respectively. Additional information is contained in the publications and work of the US Geological Survey (References 69, 70, and 71). Much of this work has been done by Hubbell.

Graf identifies the following desirable properties of tracer materials:

--A labeled and an unlabeled solid particle must react to the forces responsible for sediment motion in the same way.
--The physical and/or chemical properties of the traced particle(s) must be distinguishable and/or detectable with appropriate equipment. Depending on the desired accuracy of the sensitivity of the measuring device, the amount of tracing material necessary must be reasonable.
--The tracer on or in the solid particle should be durable, at least for the time over which the experiments or study extends.
--The tracer should not be hazardous to the biological environment.
--The cost of producing traced particles should be reasonable.

At present, there are three different types of tracers in use: radioactive tracers, paint and fluorescent tracers, and density tracers (heavy minerals).

Three different methods are available for creating radioactive tracers. One method is the irradiation method. If inactive isotope exists in a natural or aritifical solid particle, neutron irradiation in a nuclear reactor this isotope can be activated and then emits detectable radiation. Artificial sediment has been made out of glass, having the same density as quartz. Incorporated in the glass is an inactive isotope. The glass is ground and sorted, and a size distribution is selected which matches the sediment to be investigated. Immediately prior to the test, the ground glass is irradiated. Some natural sediments contain already inactive isotopes.

Another method is by sorption or coating of radioactive elements on natural sand. One technique is to add a small amount of radioactive gold chloride to the wet sediment. Hubbell and Sayve (44) used sand particles labeled with iridium-192.

Investigators concerned with the movement of larger particles have used another method. Tracers are inserted into holes which are drilled into the natural or aritificial particles and then sealed in resin.

Graf (61) recommends that isotopes be used which emit hard gamma radiation rather than soft beta radiation. Gamma radiation is only partly absorbed by sand and water, and thus it facilitates an in situ radioactivity measurement. The half-life of the tracer should be long enough to conduct the experiment but short enough to minimize interference between successive experiments. Elements known to be required in the metabolic processes of organisms should be used with utmost care, if at all.

Paint and synthetic resin finishes may be used as traces. There are, however, certain disadvantages involved. Although these finishes are inexpensive, they are limited in their use to the larger fractions of the sediment (greater than 0.2 mm). Silt and finer matter will begin to stick together. These finishes are also subject to abrasion.

A fluorescent tracer is material attached to the solid grain made up of organic dyes which fluoresce. A disadvantage of this tracing method lies in the difficulty of obtaining and analyzing the samples, which often have to be viewed in the dark with fluorescent lamps.

Among geologists, it is popular to trace heavy and light minerals. There are about 30 heavy minerals which are reasonably diagnostic of geologic source material. Some of the heavy minerals used for this purpose are hornblene, biotite, muscovite, augite, and zircon. The study of the distribution of heavy minerals is helpful for the determination of sand movement along coastlines. Heavy metals and minerals may also be introduced into the flow. Their behavior, however, is not representative of sand in general because of the greater density.

Ferromagnetic substances may also be used as tracers. Natural sand is obtained from the point under study and is mixed with fine-grained ferromagnetic material. By spreading the mixture on the bottom, information on the movement of bed load is obtained from differences in the magnetic properties of the original and labelled bed load. The principal properties of the magnetic tracer produced of the natural bed load are identical with those of the original sand.

Detection and analysis techniques vary depending on the type of tracer. Radioactive tracers may be followed in situ by suitably encased Geiger counters or scintillation detectors. For all other tracers, it is generally necessary to collect bed or suspended material samples. The tagged particles are located by visual means only (paint or resins) or by viewing under ultraviolet light (fluorescents). Heavy mineral tracers may sometimes be separated out using immersion in dense liquids such as Bromoform. Special instrumentation similar to that used for radioactive tracing is used to detect ferromagnetic material.

At this time, tracer studies seem to be relatively limited in their application to CSO studies. Radioactive tracers are the most highly developed and the easiest to detect. At the time of this writing, the environmental objectives to their use may be such that they are no longer practical. This leaves fluorescent materials, paints, ferromagnet materials, and heavy minerals. It appears from earlier portions of this report that most interest in CSO sediments centers around the midsand sizes (say 1-2 mm) down to the silt-clay range. Particles coated with fluorescent dyes could be used to gain insight into the .2 mm to 2 mm range. Paint does not appear to be useful. No current technology appears applicable to smaller particles and the silt-clay range. Dissolved fluorescent dyes such as Rhodamine WT could provide some insight into the movement of wash load (micron size) particles. Ferromagnetics and heavy minerals would only be useful if equivalent full diameter particles could be found for heavy metal pollutants such as lead or mercury.

The most promising application of tracers to CSO studies would be model verification. A study in which a large number of particles typical of a CSO outfall were released into a flow and followed could provide a useful data set. Such a study would provide insight into the correctness of model assumptions, particle transport rates, and particle dispersion along the receiving stream.

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